A REVIEW OF DIMENSIONAL INSTABILITY IN METALS

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SUMMARY

Interest in maintaining very close dimensional control in precision parts has led to increased research activity in areas usually associated with the subject of dimensional stability. Included are the related phenomena of elastic-limit determinations, microcreep, microstrain, the mechanisms which cause them, and the practical methods that can be employed to improve dimensional control.

This memorandum discusses some of the problems that arise as a result of dimensional instability, and presents information that has been made available to the Defense Metals Information Center. General recommendations are made for the processing of parts for use in applications where a high degree of dimensional stability is required.

INTRODUCTION

The dimensional stability of a material refers to its ability to maintain its original size and shape over a period of time under specified environmental conditions. Although the term is self-explanatory, it becomes necessary not only to specify the conditions to which the material is exposed, but also the accuracy to which dimensional changes are measured. Because true dimensional stability can be defined as an absolute concept, it may be more realistic to consider the degree of instability that can be measured with suitable accuracy.

Improved techniques of metrology developed during the past decade or two have increased the potential accuracy of such measurements by one or two orders of magnitude. Similarly, the requirements of industry and Government, as exemplified by the needs of missile and space systems, have become increasingly stringent. Manufacturing methods have been improved to the point where tolerances specified in microinches (millionths of an inch) are becoming commonplace; in many instances, it is important not only to manufacture a component with such precision, but also to ensure that its dimensions do not change during service. It may be expected that the standards for producing and maintaining very high degrees of precision in manufactured parts will continue to increase during the next decade, and that these will be extended into broader segments of industry not yet fully affected by the increased requirements for precision.

In the past, the distortion or dimensional instability of metals was studied mainly for the purpose of eliminating or reducing relatively large changes in dimensions in such parts as castings and die blocks. Most of these applications involved ferrous alloys, and a considerable volume of research was conducted to study the mechanisms leading to distortion, and methods for its reduction. A summary of the information available on this subject was presented in a recent DMIC report, "Control of Dimensions in High-Strength Heat-Treated Steel Parts", DMIC Report No. 163.

Additional information of a somewhat different character is needed to meet material requirements for recent developments in precision devices, such as bearings, gyros, accelerometers, and missile-guidance systems. In these applications, very high degrees of precision and dimensional stability may be needed over long periods of time. The metals involved range from the more conventional alloy steels and aluminum alloys to the newer metals – titanium, beryllium, and the refractory metals. Interest also has been shown in composite structures (sandwich, laminates, etc.) and in nonmetallics – glass, ceramics, and plastics. In general, material selection is limited by factors other than dimensional stability; examples are strength/density, resistance to corrosion, elastic modulus, and magnetic behavior. The necessity for achieving specified physical or mechanical properties in addition to stability of dimensions frequently leads to difficulties, since the processing requirements often are incompatible.

Another problem area is involved with the conditions of service under which dimensional stability is to be maintained. The influence of temperature and stress, both steady and cyclic, combined with the presence of various types of fields are the most important variables. A part of the dimensional change is (in most materials) unavoidable but predictable: thermal expansion and contraction from temperature changes, and elastic strain from stress application, for example. These effects usually can be compensated for by suitable design, and can be minimized by careful selection of material. For example, the thermal expansion can be reduced to essentially zero over a restricted temperature range by selecting a suitable alloy of the Invar type. Elastic strains can be minimized by using a material with a high elastic modulus, and by designing for low stress levels. The thermal-expansion and elastic-strain effects are essentially reversible, and are not ordinarily considered as a form of dimensional instability.

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Many of the available data have been obtained on specimens that are not subjected to external loads other than their own weight. This probably is because much of the initial research in this field was done to develop improved methods for making reference standards, such as gage blocks, rather than components subject to external loads. On the other hand, most parts in precision equipment are subjected to stress during service, even though the stress levels usually are relatively low. It has been observed that deformation, both time independent and time dependent, can occur at the microinch-per-inch level at stresses well below the conventional yield stress or proportional limit. As an example, the conventional yield strength (0.2 per cent offset) for wrought 6061 aluminum alloy was reported to be 40,000 psi, whereas the precision elastic limit was about 12,000 psi.

Studies on the mechanisms of microstrain have been carried out rather intensively in recent years. Although terminologies vary, the terms "precision elastic limit" and "microcreep limit" have been used to designate the stresses at which time-independent and time-dependent plastic flow occur. The precision elastic limit is defined as the lowest stress at which a specified residual strain (usually of 1 microinch per inch) is detected. It is ordinarily determined by loading to successively increasing stresses in tension until a residual strain is detected.[1] The microcreep limit, as defined by Hughel[2], is the lowest stress sufficient to cause a progressive increase in residual strain on three successive loadings.

As a result of the foregoing, it appears that in a stressed part, the importance of microstrain, as distinguished from true dimensional instability, must be recognized. For convenience, therefore, the total dimensional change is considered to be composed of three parts:

(1) Recoverable dimensional changes; time independent (these generally are understood and predictable, and include elastic strain, thermal expansion, and magnetostrictive strain) and time dependent (these include stress-induced and magnetically induced ordering).

(2) Plastic deformation (microstrain); this term includes the irrecoverable plastic strains, time dependent and time independent, that result from an applied stress.

(3) Dimensional instability; this term is reserved here for changes in dimensions resulting from internal stress systems or metallurgical instability (such as precipitation or phase changes); that is, changes that occur in the absence of external forces.

In the discussions that follow, these three causes of dimensional change are discussed, and available information on how they can be controlled is presented. Emphasis is placed upon the causes and effects of dimensional instability.

RECOVERABLE DIMENSIONAL CHANGES

Certain recoverable dimensional changes result from external changes in stress, temperature, and magnetic fields. Both linear and volume changes are involved; however, here we will be concerned primarily with linear changes. The elastic modulus (E) relates the magnitude of an applied stress to the corresponding elastic strain; the coefficient of linear expansion (α) relates the change of temperature to the resulting thermal strain; and the Joule magnetostriction coefficient (λ) relates the magnitude of an applied magnetic field to the corresponding linear dimensional change. Within restricted ranges of these primary variables, the dimensional changes are essentially reversible, and their magnitudes can be calculated. It remains a design problem to ensure that these changes in dimensions are suitably accounted for in each specific application.

Although these parameters (E, α, λ) are sometimes expressed as constants over restricted ranges of stress, temperature, and field strength, it is well known that these are really average values. Further, there is usually a difference in the strain path which is determined by whether the applied force, temperature, or field is increasing or decreasing. This path dependence is reflected by a hysteresis loop, indicating an absorption of energy. This energy can be related to the mechanisms involved in the strain by suitable theoretical treatment.

As pointed out previously, these reversible effects can be predicted and, to a degree, minimized individually, provided that other considerations do not preclude a free choice of material and condition. The three effects described here frequently are, to a degree, related. For example, alloys of the iron-nickel type designed for low coefficient of expansion depend upon magnetostrictive effects to accomplish this, as do similar alloys with a controlled variation of elastic modulus with temperature. Invar and Ni-Span-C are two examples of such alloys.

For most purposes, the conventional handbook values for the parameters E, α, and λ are sufficiently accurate to provide design information. Where greater accuracy is needed for a specific application, it probably will be necessary to conduct experiments on the particular material and condition to be used, since variations in composition and structure are likely to be significant. A few data on selected materials are included in the Appendix for the values of elastic modulus and expansion coefficient.

PLASTIC DEFORMATION (MICROSTRAIN)

As it is employed here, the term microstrain is defined as the irrecoverable plastic strain resulting from an applied stress. It has been pointed out for many years that the values of the elastic limit and the proportional limit of a metal, as conventionally defined, depend upon the precision of the strain measurement. Advances in measurement techniques now have progressed to the point where residual strains can be measured to a resolution of about 1×10^{-6} with resistance gages, and as great as 1×10^{-7} or 1×10^{-8} by suitable capacitance gages. The elastic limit (or precision elastic limit) usually is defined as the lowest stress for which a measurable residual strain is obtained; this is sometimes arbitrarily set at 1 microinch per inch.* In some recent studies(3), the term anelastic limit (σ_A) has been used to denote the same quantity; that is, the lowest stress at which the hysteresis loop on the stress-strain curve is not closed. Again, these values reflect the resolution of strain measurement.

The precision elastic limit is a useful quantity to the designer because it represents a limiting value for the design stress. It is necessary, however, to specify the corresponding residual strain. This ordinarily will be the smallest strain that can be detected by the strain-measuring system, or an arbitrary value such as 1 microinch per inch.

The residual microstrains corresponding to the (precision) elastic limit or the anelastic limit are considered to be essentially time independent. Studies of time-dependent deformation at microstrain levels also have been conducted. The term "microcreep limit" has been defined by Hughel as the stress just sufficient to cause progressive increase in residual strain on three successive loadings to the same stress level.(2) For beryllium, it was found that the microcreep limit was significantly higher than the precision elastic limit. In other work, microcreep in Invar and 356-T6 aluminum at room and slightly elevated temperatures has been observed at stresses near (and in some instances below) the elastic limit.(4)

*Elastic limit also has been defined(3) as the lowest stress at which a hysteresis loop is observed on the stress-strain curve after unloading.

DIMENSIONAL INSTABILITY

The term "dimensional instability", as it is used here, refers to changes in dimensions that occur over a period of time in a specimen without external loading. Data have been reported for a number of metals and alloys exposed both at constant temperature and to temperature cycling.

Mechanisms Leading to Dimensional Instability in Metals

The two primary mechanisms that cause dimensional instability in metals are reasonably well known. These are (1) metallurgical instability and (2) relaxation of residual stresses. There are, in addition, more subtle metallurgical reactions that are not so well understood. These may include the effects of ordering of interstitial and substitutional atoms, the effects of grain-boundary migration, and movements of magnetic domain walls. The effects of radiation on dimensional changes and on properties of materials, particularly fuel element materials, have been studied extensively; however, these are considered to be beyond the scope of this report. Some of the characteristics of the mechanisms leading to dimensional changes are discussed in the following sections.

Metallurgical Mechanisms

(1) Metals or alloys that do not undergo a phase change form one of the simplest classes of materials. The only apparent microstructural changes are in grain size, shape, and orientation. One metallurgical change which can cause small dimensional changes is ordering. Individual solute atoms often will tend to occupy specific positions in the solvent lattice relative to like or unlike atoms. Because these reactions are controlled by the diffusivity of the solute in question, the reaction rates are distinguished by a relatively strong temperature dependence. Small dimensional changes will follow changes in

stress, magnetization, or possibly temperature. Such reactions can be responsible for warm-up times for oscillating devices, hysteresis behavior during the stress cycle, or time dependence after reaching some fixed new temperature.

(2) An alloy that rejects a second phase from solid solution (typical of the age-hardening alloy systems) will usually undergo a gradual change in volume. The rate of the reaction is dependent upon time and temperature, and upon the degree of departure from phase equilibrium. The reaction also may be sensitive to applied stress, the application of vibrational energy, and the level of impurities in the alloy.

(3) A metal or alloy that undergoes a transformation from one allotropic form to another will change in volume. The change may be positive or negative, depending upon the relative specific volumes of the two phases. In steel, for example, the transformation from austenite to martensite results in a volume increase, the magnitude of which is dependent upon alloy composition.

(4) Combinations of the several mechanisms described above may occur concurrently. For example, a steel may exhibit simultaneously a positive volume change from the transformation of retained austenite and a negative volume change from the tempering of martensite. Thus, the net volume change may be positive, negative, or zero; it also may change from one to the other over a period of time as one mechanism becomes dominant over another.

Residual-Stress Mechanisms

Shape distortions introduced by the relaxation of residual stresses are somewhat more difficult to analyze. Residual stresses most frequently are introduced during fabrication or heat treatment, and are characteristically nonuniform. Distortion then takes place through time-dependent plastic flow. The analysis of this problem is complicated by the fact that distortions in the microinch-per-inch range can result from residual-stress changes well below the present limits of experimental stress measurement. Further, present methods for the measurement of residual stresses are quantitatively useful only for sections of simple geometry. The stress distribution and consequent distortion of parts with more complex shapes can be predicted only qualitatively.

As was pointed out previously, both metallurgical and residual-stress mechanisms are operative in most cases; therefore, the gross dimensional change measured will be the sum of the two types of distortions. Under very special conditions, it may be possible to balance the two to obtain satisfactory dimensional stability, as has been done by the National Bureau of Standards in some of its gage-block studies. More usually, it will be necessary to reduce both the metallurgical instability and the residual-stress levels to attain the necessary degree of dimensional stability.

Evaluation of Dimensional Instability

The lack of extensive data on the dimensional instability of metals and alloys reflects the difficulties encountered in making highly precise and accurate measurements. In many instances, changes in dimensions are inferred from the drift observed in a completed instrument or system rather than from actual measurements of dimensions. This frequently leads to the anomalous situation in which changes in the calibration of an instrument can be measured to a precision much greater than that of measuring dimensional changes in the parts that are causing the change.

Perhaps the most advanced metrology techniques in use today are those developed by the National Bureau of Standards for its gage-block program, whereby changes in length approaching 10^{-7} inch per inch (1/10 microinch per inch) can be detected. The basis of measurement is the interferometer, with which the length of the reference gage block is determined. An interference comparator is used to intercompare the reference and specimen gage blocks. To increase the capacity of the measurement system, an electromechanical comparator was used in conjunction with reference gage blocks. With errors minimized by statistical procedures, an accuracy of about 0.2 microinch was obtained in a 2-inch length. It should be pointed out that extremely careful control of environmental and testing conditions is vital to the attainment of this high degree of accuracy.

In studies of dimensional instability in the range of a microinch per inch per year, it is important to note the distinction between accuracy and resolution of measurements. It was pointed out earlier that the resolution of strain measurements can be as high as 1×10^{-8} inch per inch with a device such as the capacitance gage. This means that very small relative changes in length over a reasonably short time period, can be observed with comparatively simple equipment

Accuracy in the measurement of absolute lengths calls for a highly advanced measurements facility and for careful techniques of standardization.

RESEARCH ON DIMENSIONAL INSTABILITY AND ASSOCIATED PROBLEMS

An examination of the open literature and available Government reports dealing with dimensional instability reveals a comparatively small amount of useful data. This reflects in part the experimental difficulties in obtaining truly significant data, and the consequent high investment involved in such measurements. It also indicates the fact that such information frequently is regarded as highly proprietary by those industrial companies who have developed it.

The most comprehensive published compilations of data on this subject were prepared by the Instrumentation Laboratory of the Massachusetts Institute of Technology.[5,6] The data presented in these reports were collected over about a 15-year period, and have formed the basis for many of the materials-processing schedules that are in use today for the manufacture of precision devices.

A study has been in progress for a number of years at the National Bureau of Standards to improve the stability of gage-block materials.[7,8,9,10] It is restricted to those materials that are potentially useful as gage blocks (that is, with surface hardness values of at least R_C 65), and it has resulted in several materials and processing methods that produce extremely good dimensional stability.

A current research program, sponsored by the Naval Applied Science Laboratory, is being conducted by Alloyd General Corporation.[4] It presently is developing data on elastic limits, creep, and dimensional stability for a number of selected alloys including Invar, 356-T6 cast aluminum, and 310 stainless steel.

Only scattered data in addition to those listed above have been found. A number of papers in the open literature have been published, most of which deal with bearing steels, and a report on beryllium was released by the General Motors Laboratory.[2] All of the data presented in this report were taken from the sources listed above.

A number of research programs now are in progress which deal with microstrain and the mechanisms that are associated with it. These studies, which are generally basic in nature, involve the observation of microstrain effects in tension-compression, bending, and torsion, both with static and dynamic (internal friction) loading techniques. The recoverable elastic strains and the associated hysteresis loops are related to mechanisms such as the bowing of dislocation loops between pinning points. Theoretical expressions, based upon dislocation dynamics, have been developed which show promise of providing a rational basis for expressing the energy loss involved with the fundamental dislocation parameters.

The stress at which the dislocation loops break away from their pinning points likewise has been related to the stress at which a measurable residual strain is observed. This effect has been studied in various ways including direct tension and internal-friction experiments.

Much of the most recent information on microstrain was presented at a symposium sponsored by AIME,[11] for which the proceedings will serve as a reference. In summary, it appears that an improved understanding of the basic mechanisms that lead to microstrain has already been developed, and that application of these concepts to the over-all dimensional control of metals should be possible in the near future.

PROCEDURES FOR PROCESSING TO REDUCE DIMENSIONAL INSTABILITY

The degree of dimensional instability that is found in a finished metal part is influenced by (1) material composition and structure, (2) its thermal and mechanical history, and (3) the environmental conditions of exposure and use. The designer has only limited control over these factors. For example, the material selection is frequently based upon physical or mechanical-property requirements other than dimensional control: strength, density, magnetic behavior, corrosion resistance, etc. The thermal and mechanical history is likewise limited by, for example, the necessity for fabricating into a given configuration, or the need to develop a high strength or hardness by heat treatment. The conditions of environment and use likewise are largely factors that cannot be completely controlled by the designer, although he may be able to limit some of their effects; for instance, the stress level in a part may be reduced through an increase in section size.

Of the three factors, the processing treatments which determine the thermal and mechanical history are most under the control of the manu-

facturer. Thus, the attainment of a satisfactory degree of dimensional stability in a finished part will depend strongly upon the selection of suitable processing procedures. These can be related to the mechanisms leading to instability that were discussed previously. It is usual practice to stress relieve between successive machining operations, and to perform stabilizing heat treatments before and after finish machining.

The general procedures recommended in the MIT work[5] are as follows:

(1) Stress relieve

(2) Rough machine

(3) Stress relieve

(4) Perform main heat treatment

(5) Machine slightly oversize

(6) Stabilize

(7) Machine to final dimensions

(8) Stabilize.

Steps (1), (3), and (8) are indicated as optional.

There are certain general observations that can be made concerning the effects of thermal and mechanical treatments on dimensional stability:

(1) Phase equilibrium under service conditions should be approached as closely as possible, since gradual transformation is one cause of instability. In quenched and tempered steels, it is usual practice to eliminate as much retained austenite as possible from the structure by quenching to subzero temperatures before tempering. This is because definite correlations have been found between dimensional instability and the gradual transformation of retained austenite. Although repeated subzero exposures sometimes are recommended to reduce the amount of austenite retained in the structure, there is some question as to the actual effectiveness of such cyclic treatments.

Stabilization treatments generally are designed to accelerate any aging that otherwise would take place at the service temperature. For a part that is to be used at room temperature, a stabilization treatment of 24 hours at 200 F is suggested.[5] It is pointed out further that the stabilization temperature should not exceed the last temperature of the main heat treatment to avoid the loss of mechanical properties.

(2) Residual stresses leading to distortion can be introduced by drastic heating or cooling during processing. Wherever possible, parts should be heated and cooled slowly to prevent the forming of large temperature gradients. This is, of course, more important where large and complex shapes are involved. Where quenching is needed as part of a heat-treatment process, it may be desirable to reduce the severity of the quench as much as possible. For example, a quench into boiling water rather than cold water may be used after solution annealing certain age-hardening aluminum alloys.

(3) Residual stresses and consequent distortion may be introduced during machining and grinding operations. In addition, the presence of residual stresses in a heat-treated part may lead to distortion during machining due to the unequal removal of metal. This in turn may make it difficult to attain the desired dimensional tolerances, and may require that finish machining be carried out in steps, each followed by an appropriate stress-relieving treatment.

(4) The attainment of a suitable degree of stress relief without a loss of mechanical properties may require that a compromise of time and temperature be made. Newer techniques for increasing the rate of stress relief, notably by the application of ultrasonic energy, are in the development stage and may be of considerable value in the future. Temperature cycling also has been used to relieve residual stresses. This usually is done by cycling between room temperature or a moderately elevated temperature and a subzero temperature. It has been reported[5] that 10 cycles or less usually are sufficient.

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APPENDIX

COMPILATIONS OF DATA

The data presented in this Appendix have been taken from the sources cited in the preceding section. With few exceptions, no changes have been made except for the correction of a few obvious misprints.

There are some precautions that should be observed in using the information presented in these tables. First, it should be noted that even where a specific processing schedule is recommended, it does not necessarily follow that this procedure develops the optimum degree of dimensional stability for that alloy. Also, treatments leading to a high degree of stability of dimensions in samples exposed without stress do not necessarily produce the highest stability in parts that are subjected to external loads. Finally, it should be pointed out that some of the information presented here has been taken from sources that may not now be considered to be fully authenticated.

With these reservations in mind, the data presented here should provide a useful source of information for the selection and processing of parts for applications in which dimensional stability is needed. Each group of tables taken from a single source is identified, and the pertinent information on experimental techniques is presented briefly.

Data From R-95, Summary Report No. 1, "Measurement and Control of the Dimensional Behavior of Metals"

by

B. S. Lement and B. L. Averbach, Metals Processing Division, Department of Metallurgy, December, 1955. Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge 39, Massachusetts

These data were obtained using test specimens 3/8 inch in diameter and 4 inches long, with the ends spherically ground to a 2-inch radius. Length measurements were made with a 5000X comparator at 70 F. Changes in length were measured after 1/2 hour at 70 F following heat treatment for time periods up to 1 year of aging at constant temperature. The precision of the length-change determination was reported to be about 10 per cent for changes greater than about 30 microinches per inch, and about ±3 microinches for smaller changes. In the tables of data, length changes are reported to the nearest 5 microinches per inch.

Dimensional-stability data are reported for three types of exposure: (1) 70 F, (2) 160 F, and (3) after cycling 10 times between 70 F and -95 F, with a 30-minute holding period at -95 F.

TABLE A-1. DIMENSIONAL STABILITY OF PLAIN-CARBON AND LOW-ALLOY STEELS

Alloy	Spec. No.	Treatment		Rock-well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F			Aged at 160F			Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{\circ}C$
					1 mo.	3 mo.	12 Mo.	1 mo.	3 mo.	12 mo.		
1112		cold drawn	(as received)	B95	-	-	-	-	-	-	-	
	17S-1,2,3	stress relieve	800F, 1 hr., A.C. -(R)	B95	+ 5	0	- 5*	- 5	- 5	- 5*	0	11.8
	17S-4,5,6		1200F, 1 hr., A.C. -(R)	B77	-10	-10	-10*	- 5	- 5	- 5*	- 5	11.8
1020	1L**-1,2,3	anneal	1650F, 1hr., F.C.	B74	-15	-15	-25	-10	-10	-15	-15	11.4
	1T***-1,2,3	anneal	1650F, 1hr., F.C.	B74	- 5	- 5	-10	-20	-25	-40	-15	
X1020	16-1,2,3	cold drawn	(as received)	B93	- 5	-10	-15	- 5	-10	-15	-15	
	16-4,5,6	stress relieve	1200F, 1hr., A.C.	B62	-15	-20	-30	- 5	- 5	-10	0	
	16-7,8,9	normalize	1600F, 1/2hr., A.C.	B74	-10	-10	-15	-45	-50	-65	-25	
	16-10,11,12	harden	1600F, 1/2hr., B.Q.	C40	+40	+50	+65	+100	+105	+120	+60	
	16-13,14,15	temper	300F, 1/2 hr., A.C.	C40	- 5	- 5	- 5	+15	+20	+30	+10	11.6
1045	5-16,17,18	cold drawn	(as received)	B94	- 5	-10	-15	0	0	-20	- 5	
	5-19,20,21	stress relieve	1200F, 1 hr., F.C. -(R)	B93	- 5	- 5	-10	0	0	- 5	- 5	
	5-7,8,9	anneal	1550F, 1/2 hr., F.C.	B90	- 5	- 5	-	- 5	- 5	-	- 5	11.2
	5-10,11,12	stabilize	300F, 1 hr., A.C. -(R)	B93	0	0	-	- 5	- 5	-	- 5	
	5-22,23,24	normalize	1600F, 1/2 hr., A.C.	B95	-25	-35	-45	-20	-25	-35	-15	
	5-6	draw	800F, 1hr, A.C.	B95	- 5	-10	-	-	-	-	-	
	5-25,26,27	harden	1525F, 1/2hr., B.Q.	C56	-30	-50	-70	+55	+55	+55	-205	
	5-28,29,30	temper	300F, 1hr., A.C.	C58	- 5	- 5	-10	-25	-30	-35	-15	
1144	13-7,8,9	anneal	1550F, 1/2 hr., F.C.	B95	0	0	-	0	0	-	0	
	13-4,5,6	normalize	1600F, 1/2 hr., A.C.	B95	-15	-20	-	-10	-15	-	-	
	13-6	draw	800F, 1 hr., A.C.	B95	- 5	- 5	-	-	-	-	-	
		harden	1550F, 1/2 hr., O.Q.									
	13-1,2,3	temper	1100F, 1 hr., W.Q.	C23	0	0	0*	0	0	-	- 5	11.1
4140	6-9,10,11	anneal	1550F, 1/2hr., F.C. -(R)	B95	0	- 5	-	0	- 5	-	+ 5	11.4
	6-6,7	normalize	1600F, 1/2 hr., A.C.	C22	+20	+25	+30	+ 5	+25	-	-	
	6-8	draw	800F, 1/2 hr., A.C.	C33	- 5	- 5	-	-	-	-	-	
	6-4	harden	1550F, 1/2 hr., O.Q.	C54	+90	+100	+100*	-	-	-	-	
4140	6-5	subzero	-320F, 1hr., A.H.	C54	-10	-10	-10*	-	-	-	-	
		harden	1550F, 1/2hr., O.Q.									
	6-13,14,15	temper	300F, 2hrs., A.C.	C54	- 5	0	0*	+ 5	+15	+20*	0	
	6-16,17,18		1000F, 2hrs., A.C. -(R)	C38	-10	-10	-10*	- 5	- 5	- 5*	- 5	
	6-1,2,3		1100F, 1hr., W.Q.	C33	-25	-25	-35	-35	-45	-60	-15	11.1
4340	10-4,5,6	anneal	1550F, 1/2hr., F.C. -(R)	B93	0	0	-	0	0	-	0	11.2
	10-7,8,9	harden	1550F, 1/2hr., O.Q.	C55	+90	+90	+90*	-25	-30	-	+200	
	10-15,16,17	temper	300F, 2hrs., A.C.	C56	- 5	- 5	+ 5*	+15	+25	+40*	+10	
	10-1,2,3		1100F, 1hr., W.Q.	C35	- 5	- 5	-10*	-15	-20	-20	-20	10.9
		austenitize	1550F, 1/2hr.									
	10-18,19,20	martemper	H.Q. to 600F, A.C.	C48	+ 5	+ 5	+10*	+25	+35	+60	+70	
1070	3-7,8,9	anneal	1450, 1/2hr., F.C.	B90	-15	-20	-20	- 5	- 5	-10	-20	
		normalize	1600F, 1/2 hr., A.C.									
	3-4,5,6	draw	1100F, 1 hr., A.C.	B94	-15	-15	-20	- 5	- 5	- 5	- 5	
		harden	1500F, 1/2 hr., W.Q.									
	3-1,2,3	temper	300F, 1hr., A.C.	C66	-30	-20	-30	-25	-25	-30	-15	

*6 months of aging
**L - longitudinal direction
***T - transverse direction
(R) - recommended treatment

F.C. - furnace cool
A.C. - air cool
O.Q. - oil quench
W.Q. - water quench
B.Q. - brine quench
H.Q. - hot quench
A.H. - air heat

TABLE A-2. DIMENSIONAL STABILITY OF TOOL STEELS

Alloy	Spec. No.	Treatment		Rock well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{\circ}C$
10100	S-7,8,9	anneal	1450F, 1hr., F.C.	B87	-10	-15	-15	-15	-20	-20	-20	
		normalize	1550F, 1/2hr., A.C.									
	S-4,5,6	draw	1100F, 1 hr., A.C.	B97	-10	-10	-15*	-5	+5	+5	-15	
		harden	1450F, 1/2hr., W.Q.									
	S-1,2,3	temper	300F, 1hr., A.C.	C65	-5	-10	-15	10	-5	-	+30	
10100	K-57,62	harden	1450F, 1/2hr, W.Q.	C66	-175	-265	-405	-	-	-	-	
	K-58,63	temper	300F, 1hr., A.C.	C65	-5	-5	-10	-	-	-	-	
	K-79,85		350F, 1hr., A.C.-(R)	C64	-5	-5	-10	-	-	-	-	11.8
	K-115		400F, 1hr., A.C.	C63	0	-5	-5	-	-	-	-	
	K-116		500F, 1hr., A.C.	C62	0	-5	-5	-	-	-	-	
		harden	1450F, 1/2hr., W. Q.									
	K-80	subcool	-320F, 1hr., A.H.	C67	-240	-350	-525	-	-	-	-	
	K-81	temper	300F, 1hr., A.C.	C68	-5	-10	-15	-	-	-	-	
	K-154		400F, 1hr., A.C.-(R)	C64	-5	-5	-5	-	-	-	-	
	K-155		500F, 1hr., A.C.-(R)	C60	-5	-5	-5	-	-	-	-	
		harden	1450F, 1/2hr., W.Q.									
		temper	300F, 1hr., A.C.									
	K-83	subcool	-320F, 1hr., A.H.	C66	-10	-10	-15	-	-	-	-	
	K-84	temper	300F, 1hr., A.C.	C66	-10	-10	-15	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		quench	oil at 125F, A.C.									
	K-157	temper	300F, 1hr., A.C.	C66	-5	-5	-	-	-	-	-	
	K-158		400F, 1hr., A.C.	C63	-10	-15	-	-	-	-	-	
Mangan-ese Die	M-44,46	harden	1450F, 1/2hr., O.Q.	C64	-30	-50	-90	-	-	-	-	
	M-45,47	temper	300F, 1hr., A.C.-(R)	C65	0	0	0	-	-	-	-	11.9
	M-56	subcool	-320F, 1hr., A.H.	C63	-10	-10	-15	-	-	-	-	
		temper	300F, 1hr., A.C.	C62	-5	-5	-10	-	-	-	-	
		harden	1450F, 1/2hr., O.Q.									
	M-54	subcool	-320F, 1hr., A.H.	C65	-90	-130	-185	-	-	-	-	
	M-55	temper	300F, 1hr., A.C.	C68	-5	-5	-10	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		quench	oil at 125F, A.C.									
	M-57,62,65, 67,73,75	temper	300F, 1hr., A.C.	C62	+15	+20	-	-	-	-	-	
	M-76		400F, 1hr., A.C.	C61	+5	+5	-	-	-	-	-	
		austenitize	1450F, 1/2hr.									
		marquench	M.Q. to 450F, A.C.									
	M-70	temper	300F, 1hr., A.C.	C63	+10	+15	-	-	-	-	-	
	M-71		400F, 1hr., A.C.	C60	0	-5	-	-	-	-	-	
Tungsten Die	G-23,25	harden	1600F, 1/2hr., O.Q.	C66	-100	-155	-260	-	-	-	-	
	G-24,26	temper	300F, 1hr., A.C.-(R)	C55	0	0	0	-	-	-	-	11.6
	G-35	subcool	-320F, 1hr., A.H.	C65	-10	-10	-15	-	-	-	-	
	G-36	temper	300F, 1hr., A.C.	C65	-5	-5	-10	-	-	-	-	
		harden	1600F, 1/2hr., O.Q.									
	G-32	subcool	-320F, 1hr., A.H.	C66	-175	-250	-360	-	-	-	-	
	G-33	temper	300F, 1hr., A.C.	C66	-5	-5	-10	-	-	-	-	

TABLE A-2. (Continued)

Alloy	Spec. No.	Treatment		Rockwell Hardness	Microinch per Inch Length Change in Time and Cycle Stability Tests: Aged at 70F 1mo.	Aged at 70F 3mo.	Aged at 70F 12mo.	Aged at 100F 1mo.	Aged at 100F 3mo.	Aged at 100F 12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{o}C$
52100		harden	1550F, 1/2hr., O.Q.									
		subcool	-75F, 1hr., A.M.									
	170-1,2,3	double temper	300F, 1hr., A.C. (2)	C66	-5	-10	-10*	-10	-15	-25*	-5	11.0
52100		harden	1550 F, 1/2hr., O.Q.									
	2L**-1,2,3	temper	300F, 1hr., A.C.	C64	-5	0	0	+10	+15	-	+10	
	2T***-1,2,3	temper	300F, 1hr., A.C.	C64	-5	-5	0	+10	+20	-	+15	
52100	T-11	harden	1550F, 1/2hr., O.Q.	C64	-40	-80	-110	-	-	-	-	
	T-56,60	temper	250F, 10hrs., A.C. - (R)	C65	0	0	-	-	-	-	-	
	T-48,63		300F, 1hr., A.C.	C64	0	0	0	-	-	-	-	
	T-54		400F, 1hr., A.C. - (R)	C62	0	0	0	-	-	-	-	11.0
			500F, 1hr., A.C.	C60	0	0	0	-	-	-	-	
		harden	1550F, 1/2hr., O.Q.									
	T-39,42	subcool	-320F, 1hr., A.M.	C95	-90	-35	-105	-	-	-	-	
	T-56	temper	250F, 10hrs., A.C.	C66	0	0	-	-	-	-	-	11.0
	T-40		300F, 1hr., A.C.	C64	-5	-5	-5	-	-	-	-	
			400F, 1hr., A.C.	C61	-5	-5	-5	-	-	-	-	
			500F, 1hr., A.C.	C59	0	0	0	-	-	-	-	
		harden	1550F, 1/2hr., O.Q.									
		temper	300F, 1hr., A.C.									
	T-72	subcool	-320F, 1hr., A.M.	C64	-5	-5	-10	-	-	-	-	
	T-73	temper	300F, 1hr., A.C.	C65	0	-5	-5	-	-	-	-	
		austenitize	1550F, 1/2 hr.,									
		quench	oil to 125F, A.C.									
	T-22,55	temper	300F, 1hr., A.C.	C65	+15	+25	-	-	-	-	-	
	T-51		400F, 1hr., A.C.	C62	0	-5	-	-	-	-	-	
52100		austenitize	1550F, 1/2 hr.									
		marquench	H.Q. to 350F, A.C.									
	T-35, 53	temper	300F, 1hr., A. C.	C64	0	0	-	-	-	-	-	
	T-50		400F, 1hr., A.C.	C63	-5	-5	-	-	-	-	-	
		austenitize	1550F, 1/2hr									
		marquench	H.Q. To 450F, A.C.									
		subcool	-320F, 1hr., A.M.									
	T-69	temper	250F, 10 hrs., A. C.	C66	-5	-5	-	-	-	-	-	
	T-70		300F, 1hr., A.C.	C64	-5	-5	-	-	-	-	-	
	T-71		400F, 1hr., A.C.	C63	-5	-5	-	-	-	-	-	
52100	S3-1	harden	1550F, 1/2hr., O.Q.		+80	+70	-	-	-	-	-	
	S3-2	subcool	-320F, 1hr., A.M.		-110	-140	-	-	-	-	-	
		harden	1550F, 1hr., O.Q.									
	S3-3	temper	200F, 1hr., A.C.		+45	+50	-	-	-	-	-	
	S3-4		300F, 1hr., A.C.		-5	-10	-	-	-	-	-	12.5
1C-5Cr	63-2	harden	1800F, 1/2hr., A.C.	C56	+250	+225	+220*	-	-	-	-	
	63-3,4,5	temper	300F, 2hrs., A.C.	C54	-5	-5	-5*	-10	-10	-10*	+65	12.3
	63-6,7,8		950F, 2hrs., A.C.	C49	+440	+470	+490	+425	+430	+440*	+600	10.9
High C,	F-33	harden	1900F, 1/2hr., A.C.	C65	+15	+5	-10	-	-	-	-	
High Cr	F-46	temper	300F, 2hrs., A.C.-(R)	C61	0	-5	-10	-	-	-	-	
			900F, 2hrs., O.Q.	C63	+30	+35	+30	-	-	-	-	
		harden	1900F, 1/2hr., A.C.									
		triple temper	900F, 1hr., O.Q. (3)	C63	+310	+370	-	-	-	-	-	
	F-57	stress relieve	450F, 1hr., A.C.	C61	+150	+185	-	-	-	-	-	

TABLE A-2. (Continued)

Alloy	Spec. No.	Treatment		Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -95F	Thermal Expans. Coef. 10⁻⁶/°C
High C,		harden	1800F, 1/2hr., A.C.									
High Cr	F-46	subcool	-125F, 1hr., A.H.	C66	-50	-80	-120	-	-	-	-	
		temper	650F, 1hr., O.Q.	C63	-5	-10	-	-	-	-	-	
	F-47		930F, 2hrs., A.C.	C61	+45	+55	+60	-	-	-	-	
		harden	1900F, 1/2hr., A.C.									
		subcool	-320F, 1hr., A.H.									
		triple temper	950F, 1 hr., O.Q. (3)									
	F-60		450F, 1hr., A.C.	C62	+95	+125	-	-	-	-	-	
		harden	1900F, 1/2hr., A.C.									
		subcool	a. -320F, 1hr., A.H.									
		temper	b. 950F, 1 hr., O.Q.									
		cycle	c. Repeat steps a and b four times									
	F-62		d. 450F, 1 hr., A.C.-(R)	C60	0	0	-	-	-	-	-	10.2
High C, High Cr	64-8,9,10	anneal	1600F, 2 hrs., F.C.	B88	-8	-5	-50*	0	0	0*	+5	
	64-1	harden	1800F, 1/2 hr., O.Q.	C65	+100	+90	+70*	-	-	-	-	
	64-2,3,4	temper	300F, 2 hrs., A.C.-(R)	C63	0	0	0*	-10	-10	-10*	-5	10.3
	64-5,6,7		900F, 2 hrs., A.C.	C58	+280	+300	+340*	+380	+385	+410*	+435	10.0
M-2 High Speed	E-9	air harden	2220F, 3 mins., A.C.	C60	-5	-25	-50	-	-	-	-	
	E-8,10	harden	2220F, 3 mins., O.Q.	C65	-70	-100	-150	-	-	-	-	
		temper	1050F, 2 1/2 hrs., O.Q.									
	E-16	stress relieve	600F, 1 hr., A.C.	C64	-5	0	+5	-	-	-	-	
		harden	2220F, 3 min., O.Q.									
	E-11	temper	1050F, 2 1/2 hrs., A.C.	C65	+25	+35	+50	-	-	-	-	
	E-13	stress relieve	600F, 1hr., A.C.	C65	+10	+15	+20	-	-	-	-	
	E-12		900F, 1hr., A.C.	C65	+20	+30	+45	-	-	-	-	
M-2 High Speed		harden	2220F, 3min., O.Q									
		double temper	1050F, 2 1/2 hrs., A.C.(2)									
	E-14	stress relieve	600F, 1hr., A.C.	C64	+10	+10	+15	-	-	-	-	
		harden	2220F, 3min., O.Q.									
		triple temper	1050F, 2 1/2hrs., A.C.(3)									
	E-15	stress relieve	600F, 1hr., A.C.	C65	+10	+10	-	-	-	-	-	
		harden	2220F, 3mins. O.Q									
		triple temper	1050F, 2 1/2 hrs., O.Q.(3)									
	E-25	stress relieve	600F, 1hr., A.C.	C65	5	5	-	-	-	-		
	E-26		900F, 1hr., A.C.-(R)	C65	0	0	-	-	-	-	-	
		harden	2220F, 3mins., O.Q.									
	E-24	subcool	-320F, 1hr., A.H.	C66	-190	-235	-	-	-	-	-	
		temper	1050F, 2 1/2hr., A.C.									
	E-17	stress relieve	600F, 1hr., A.C.	C64	+25	+35	-	-	-	-		
		harden	2220F, 3min., O.Q.									
		subcool	-320F, 1hr., A.H.									
		triple temper	1050F, 2 1/2hrs., O.Q.(3)									
	E-18	stress relieve	600F, 1hr., A.C.	C64	0	0	-	-	-	-	-	
	E-19		900F, 1hr., A.C.-(R)	C64	0	0	-	-	-	-	-	10.5

* 6 months of aging
** L - longitudinal direction
*** T transverse direction
(R) - recommended treatement

F.C. - furnace cool
A.C. - air cool
O.Q. - oil quench
W.Q. - water quench
H.Q. - hot quench
A.H. - air heat

TABLE A-3. DIMENSIONAL STABILITY OF STAINLESS STEELS

Alloy	Spec. No	Treatment		Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	Aged at 70F 3mo.	Aged at 70F 12mo.	Aged at 160F 1mo.	Aged at 160F 3mo.	Aged at 160F 12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{\circ}C$
302	15-11,12,13	quench anneal	1950F, 1/2hr., W.Q.	B79	- 5	- 5	-10	-10	-15	-20	-80	
	15-8,9,10	stress relieve	600F, 1hr., A.C.	B79	0	-	-	C	-	-	+ 5	16.3
	15-14,15,16		750F, 1hr., A.C.	B79	0	0	- 5	- 5	-10	-15	-10	
303		cold drawn	(as received)									
	7-28,29,30	stress relieve	750F, 1hr., A.C.	B98	-10	-15	-20	- 5	-10	-20	- 5	
	7-4,2,3	quench anneal	1950F, 1/2hr., W.Q.	B82	- 5	- 5	-10	-20	-30	-45	-50	
	7-13,14,15	stabilise	200F, 20hrs., A.C.	B83	0	-	-	- 5	- 5	-	-25	
	7-22,23,24	quench anneal	1950F, 1/2hr., W.Q.	B83	-10	[illegible]	-10*	-10	-10	-10*	-40	
	7-6,7,8	stress relieve	600F, 1hr., A.C.	B82	- 5	- 5	-	- 5	- 5	-	-10	
	7-25,26,27		750F, 1hr., A.C.	B82	0	0	0	-10	-10	-15	-15	
		quench anneal	1950F, 1/2hr., W.Q.									
		stress relieve	600F, 1hr., A.C.									
	7-19,20,21	stabilise	200F, 20hrs., A.C.-(R)	B82	- 5	- 5	0*	- 5	- 5	-	- 5	18.1
310	25-4,5,6	quench anneal	1950F, 1/2hr., W.Q.	B84	-10	-10	-10	- 5	- 5	- 5	-20	
	25,7,8,9	stress relieve	750F, 1hr., A.C.	B84	- 5	- 5	- 5	- 5	- 5	-10	-20	14.6
410	24,11,12,13	anneal	1600F, 2 hrs., F.C.									
			to 1100F, A.C.	B78	- 5	- 5	-10*	-10	-10	-10*	-15	
	24-4	harden	1800F, 1/2 hr., O.Q.	C47	+15	+10	+ 5*	-	-	-	-	
	24-1,2,3	temper	450F, 1hr., A.C.-(R)	C46	- 5	- 5	-10	- 5	- 5	- 5	-10	
	24-5,6,7,14		800F, 1hr., A.C.-(R)	C41	0	0	- 5	- 5	- 5	-10	- 5	10.2
	24-8,9,10		1200F, 4hrs., A.C.	C22	-10	-10	-15*	- 5	- 5	-10*	-15	
440C	39-6,7,8	anneal	1650F, 2hrs., F.C.	B94	- 5	- 5	- 5*	0	0	0*	0	
		harden	1900F, 1/2hr., O.Q.	C63								
	39-3,4,5	temper	500F, 1hr., A.C.-(R)	C61	0	- 5	-10*	0	0	- 5*	- 5	10.2

*6 months of aging W.Q. -water quench F.C. - furnace cool
(R) recommended treatment A.C. -air cool O.Q. - oil quench

TABLE A-4. DIMENSIONAL STABILITY OF NICKEL ALLOYS

Alloy	Spec. No.	Treatment		Rock-well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -85F	Thermal Expans. Coef. $10^{-6}/°C$
A-Nickel	55-1	cold drawn	(as received)	B83	0	-5	-5*	-	-	-	-	
	55-2,3,4	quench anneal	1525F, 1/2 hr., W.Q.	B36	-65	-70	-70	-30	-	-	+15	12.3
Z-Nickel		cold drawn	(as received)	C29								
	54-1,2,3	age harden	1000F, 9hrs., F.C.									
			to 900F, A.C.	C40	0	0	-	-	-	-	-5	12.4
Inconel	57-1	cold drawn	(as received)	C20	-5	-10	-10*	-	-	-	-	
Inconel	173-1,2,3	anneal	1700F, 1hr., F.C.	B71	0	0	0	0	0	0	+3	12.5
	173-4,5,6	stabilize	200F, 24hrs., A.C.-(R)	B71	0	0	-5	0	0	-5	0	12.7
Inconel		anneal	1700F, 1hr., F.C.									
	185-1,2,2,4	stabilize	200F, 24hrs., A.C.-(R)	B79	-5	-5	-	0	0	-	-5	12.6
Inconel X	58-1	cold drawn	(as received)	C27	0	-10	-10*	-	-	-	-	
Monel	59-1	cold drawn	(as received)	B96	0	-10	-15*	-	-	-	-	13.6
K-Monel	56-1A	cold drawn	(as received)	A64	0	-5	-5*					
		age harden	1000F, 9hrs., F.C.									
	56-1,2,3		to 900F, A.C.	C37	-5	-5	-	0	-5	-	0	13.4
Hastelloy B		quench anneal	2100F, 1hr., W.Q.									
	179-1,2,3	quench anneal	1950F, 1hr., W.Q.	B95	-10	-15	-15*	-35	-40	-40*	-15	
	179-4,5,6	stress relieve	600F, 1hr., A.C.-(R)	B95	0	0	0	0	0	0*	0	10.4
Ni-Span Lo 45	60-1A	cold rolled	(as received)	A63	-5	-10	-10*	-	-	-	-	
		solutionize	1800F, 1 1/4hr., W.Q.									
	60-1,2,3	age	1250F, 21hrs., A.C.	C34	-10	-15	-15*	-15	-15	-20*	-10	
42Ni-58Fe	77-1A	quench-anneal	1525F, 1/2 hr., W.Q.	B72	0	0	0	-10	-	-	-	4.5
	77-2,3											
Ni-Span-C	61-1	cold drawn	(as received)	A80	-5	-5	-5*	-	-	-	-	
		solutionize	1800F, 1 1/4 hr., W.Q.									
	61-1,2,3	age	1250F, 21hrs., A.C.	C29	-10	-10	-10*	-15	-15	-15*	-30	7.2
Regular Invar	50L-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-15	-20	-20	+40	+5	-70	-75	
	50T-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-45	-40	-25*	-10	-20	-30*	+20	
Regular Invar	51-17,18,19	anneal	1525F, 1hr., F.C.	B77	-25	-25	-	+5	+5	-	-15	
	51,1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B77	-5	-5	-	+25	+25	-	-15	
	51-2C,D	stress relieve	150F, 1 mo., W.Q.	B77	0	-5	-5	-	-	-	-	
	51-4,5,6		250F, 1hr., F.C.	B77	-10	-5	0	-10	0	-	-10	
	51-10		300F, 1 mo., W.Q.	B77	+5	+5	+5	-	-	-	-	
	51-9		400F, 1 mo., W.Q.	B77	+10	+10	+10	-	-	-	-	
	51-8		600F, 1 mo., W.Q.	B77	+5	+5	-	-	+30	-	-	
	51-20		600F, 1 hr., W.Q.	B77	-	-	-	+25	+25	+25*	-	
		stress relieve	1200F, 1 hr., A.C.									
	51-22,23,24	stabilize	200F, 48hrs. A.C.		-5	-5	-5*	-5	0	0*	-10	

TABLE A-4. (Continued)

Alloy	Spec. No.	Treatment		Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{\circ}C$
Free Cut	52-1,2,3	cold drawn	(as received)	B98	0	0	0	+15	0	+50*	-20	
Invar	52-42,42	stabilize	200F, 20 hrs., A.C.	B98	- 5	- 5	-	- 5	- 5	-	-	
		cold drawn	(as received)	B95								
	52-4,5,6	stress relieve	1200F, 1 hr., F.C.	B95	-15	-20	-25	0	- 5	-10*	- 5	
	52-31		200F, 1 hr., A.C.	B95	-15	-20	-20*	-	-	-		
	52-32,33,34		200F, 20hrs., A.C.-(R)	B95	- 5	- 5	- 5*	0	- 5	- 5*	-10	1.5
	52-7-8,9		300F, 1 hr., F.C.	B95	-15	-20	-30	-20	-20	-35	-15	
	52-30		400F, 1 hr., A.C.	B95	- 5	- 5	- 5*	-	-	-	-	
	52-10,19,20	quench anneal	1525F, 1/2 hr., W.Q.	H78	- 5	-10	-10	-40	-	-	-10	
	52-19	stabilize	158F, 1mo., W.Q.	H78	0	0	0	-	-	-	-	
	53-36,37,38		200F, 20 hrs., A.C.	B78	-35	-35	-30*	- 5	- 5	-	0	
	52-15		200F, 1 mo., W.Q.	H78	0	0	- 5	-	-	-	-	
	52-11		250F, 1 hr., F.C.	B78	- 5	-10	-10	-	-	-	-	
	52-18C		300F, 1 mo., W.Q.	H78	-10	-10	-15	-	-	-	-	
	52-17		400F, 1 mo., W.Q.	B78	0	- 5	- 5	-	-	-	-	
	52-21		600F, 1mo., W.Q.	H78	- 5	- 5	-10	-	-	-	-	
	52-27,28,29	anneal	1525F, 1/2 hr., F.C.	H78	-10	- 5	-20*	- 5	- 5	- 5*	-15	
	52-39,40	stabilize	200F, 20hrs., A.C.	H77	- 5	5	-	- 5	- 5	-	-	
Free Cut	66-10,11,12	cold drawn	(as received)	H87								
Invar		stress relieve	1200F. 1hr., F.C.									
		stabilize	200F, 48hrs., A.C.-(R)	B89	-10	-10	-10*	- 5	- 5	0*	-35	2.0
	66-7,8,9	quench-anneal	1525F,1/2 hr. W.Q.									
		stress relieve	1200F, ½ hr., A.C.									
		stabilize	200F, 48hrs., A.C.(R)	B79	- 5	- 5	-10*	- 5	0	0*	-10	
	66-1,2,3	quench-anneal	1525F, 1/2 hr., W.Q.	B78	-20	-20	-25*	-20	-20	-20*	-25	
	4,5,6	stress relieve	600F, 1 hr., A.C.									
		stabilize	200F, 48 hrs., A.C.	B78	-10	-10	-15*	-10	-10	-15*	-10	
Super		cold drawn	(as received)	B98								
Nilvar	9-1,2,3	anneal	1525F, 1hr., F.C.	B97	-10	-	-	- 5	-	-	+25	
		stress relieve	1200F, 1hr., F.C.									
	9-5	stabilise	200F, 24hrs., A.C.									0.8
32Ni-68Fe	78-1,2,3	quench-anneal	1525F, 1/2hr., W.Q.	B83	0	+ 5	+ 5	+ 5	-	-	-55	3.4
Ni-Span-Ni	62-1	cold drawn	(as received)	A62	0	-10	-15*	-	-	-	-	
		solutionize	1800F, 1 1/4 hrs., W.Q.									
	62-1,2,3	age	1250F, 20hrs., A.C.-(R)	C30	- 5	- 5	- 5*	-10	-10	-10*	-10	15.5

* 8 months of aging
(R)- Recommended Treatment

W.Q. - water quenched
F.C. - furnace cooled
A.C. - air cooled

TABLE A-6. DIMENSIONAL STABILITY OF COPPER ALLOYS

Alloy	Spec. No.	Treatment		Rockwell Hardness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	Aged at 70F 3mo.	Aged at 70F 12mo.	Aged at 160F 1mo.	Aged at 160F 3mo.	Aged at 160F 12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/^{o}C$
85Cu-5Zn -5Sn-5Pb	29-1,2,3	cast	(as received)	F46-71	-10	-45	-45	-10	- 5	- 5*	-15	17.2
Beryllium Copper		solutinize	1450F, 2 hrs., W.Q.									
	31-4,5,6	age	600F, 2 hrs., A.C.	C37	0	0	-	0	- 5	-	- 5	15.9
		solutionize	1400F, 1/2 hr., W.Q.									
	31-1,2,3	age	625F, 3hrs., A.C.	C38	-15	-15	-20	0	0	-	-10	
Beryllium Copper	47-1,2,3	cast	(as received)	B72	-15	-20	-	-10	-10	-10*	-10	15.3
		solutionize	1450F, 2hrs., W.Q.									
	47-4,5,6	age	600F, 2hrs., A.C.	C36	-	-	-	-	-	-	-	16.0
70Cu - 30Zn	41-1,2,3	cast	(as received)	F30-50	-30	-30	-30	-35	-45	-50*	-30	18.1
Aluminum Bronze	43-1,2,3	cast	(as received)	F65-90	-10	-15	-15*	-10	-15	-	- 5	
		harden	1625F, 1hr., W.Q.									
	43-4,5,6	temper	1000F, 1hr., W.Q.	B74	-10	-10	-	-10	-15	-	- 5	16.2
Nickel Silver	46-1,2,3	cast	(as received)	F80	-30	-30	-35*	-10	-15	-	-20	15.5

* 6 months of aging

(R)- recommended treatment

W.Q. - water quench

A.C. - air cool

TABLE A-6. DIMENSIONAL STABILITY OF ALUMINUM ALLOYS

Alloy	Spec. No.	Treatment		Rock-well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/°C$
2017 (17 S)		solutionize	940F, 2hrs., B.W.Q.									
	163-1,2,3	age	72F, 96 hrs., A.C.	B40	0	-10	-15	-10	-15	-20	-5	
		solutionize	940F, 1/2 hr., W.Q.									
	143-7,8,9	age	350F, 11hrs., A.C.	B57	-5	-5	-	-5	-5	-	0	21.5
2024 (24 S)	21-15	anneal	775F, 1 hr., F.C.	F41	-10	-10	-15	-	-	-	-	
	21-1,2,3	solutionize	920F, 1/2 hr., W.Q.	B52-70	+95	+80	+65*	+25	+25	+20*	+65	
	21-16,17,15,22	age	375F, 12hrs., A.C.-(R)	B71	-5	-5	-5	+5	+10	+10	-5	21.[illegible]
	21-19,20,21		400F, 1hr., A.C.	B70	+5	+10	+20	+5	+10	+15	+15	
	21-25,26,27		400F 2 hrs., A.C.	B72	+5	+5	-	-[illegible]	-5	-	0	
		solutionize	950F, 1/2 hr., W.Q.									
	21-7,8,9	age	200F, 20 hrs., A.C.	B72	-10	-	-20*	-10	-	-10*	-45	
40 E	160-1,2,3	age	350F, 10 hrs., A.C.	B60	-20	-	-	-30	-	-	+5	
40 H	141-19,20,21	age	250F, 52 hrs., A.C.	B79	-5	-10	-	-30	-35	-	-10	
		solutionize	920F, 10 hrs., W.Q.									
	141-1,2,3	age	300F, 4hrs., A.C.	B45	-20	-	-	-45	-	-	-10	[illegible]1.8
	141-10,11,12		300F, 7 hrs., A.C.	B62	-5	-5	-	-15	-35	-	0	
4043 (43)	26-1,2,3	cast	(as received)	F70	-	-40	-55*	-	-15	-20*	-65	
	26-4,5,6		650F, 2hrs., F.C.	B73	-15	-20	-25	-25	-30	-35	-15	21.3
	26-7,8,9		650F, 2hrs., W.Q.	B72	-10	-15	-20*	-30	-35	-40*	-190	
6061 (61 S)	18-4	anneal	750F, 2 hrs., F.C.	F17	-10	-10	-15	-	-	-	-	
	18-5,6,7	solutionize	970F, 1/2 hr., W.Q.	B36	+20	+30	+35*	+70	+80	-	-25	20.0
	18-14,15,16	age	300F, 22 hrs., A.C.	B60	-10	-10	-	-25	-30	-	-40	
	18-17,18,19		350F, 6 hrs., A.C.	B55	-15	-15		+5	+5	-	-20	
7075 (75 S)	19-4	anneal	775F, 1 hr., F.C.	F50	-5	-5	-10	-	-	-	-	
	19-5,6,7	solutionize	900F, 1/2 hr., W.Q.	B45-60	-10	-30	-55	-150	-200	-275	-50	
		age	315F, 8 hrs., A.C.									
	19-8,9,10	stabilize	210F, 4 hrs., A.C.	B91	-25	-20	-20	-	-	-	-30	22.1
195	27-1,2,3	cast	(as received)	F66	-20	-25	35	-	-25	-30*	+10	
	27-5,6,7	solutionize	960F, 2 hrs., B.W.Q.					-90	-80	-80	-30	
	27-14,15,16	age	310F, 4 hrs., A.C.	B48	-15	-20	-	-35	-43	-	-15	
	27-11,12,13		310F, 22 hrs., A.C.	F70	-10	-10	-	-15	-5	-	-15	22.[illegible]
	27-4	anneal	650F, 2 hrs., F.C.	F26	-55	-60	-60*	-	-	-	-	
35[illegible]	28-1,2,3	cast	(as received)	F70	-	-	-	-	+25	-	+15	
	28-4,5,6	stress relieve	440F, 8hrs., F.C.	F76	-5	-5	-	0	+15	-	-15	
		solutionize	1000F, 12 hrs., W.Q.									
	28-20,21,22	age	460F, 8hrs., F.C.	B30	-5	-5	-	+5	+5	-	-10	
		solutionize	1000F, 2hrs., W.Q.									
	28-17,18,19	age	640F, 8 hrs., A.C.	B30	-5	-10	-	-5	0	-	-20	
		solutionize	1000F, 2 hrs., B.W.Q.									
	28-8,9,10	age	310F, 4hrs., A.C.-(R)	B58	0	0	-	-5	0	-	-5	20.8
Apex Term-alloy 6	152-1,2,3,4	stress relieve	400F, 8hrs., A.C.	F81	0	-5	-5	-10	-10	-20*	+[illegible]	21.2

* 6 months of aging
(R) - recommended heat treatment
B.W.Q. - boiling water quench
A.C. - air cool
W.Q. - water quench
F.C. - furnace cool

TABLE A-7. DIMENSIONAL STABILITY OF MAGNESIUM ALLOYS

Alloy	Spec. No.	Treatment		Rock well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: Aged at 70F 1mo.	3mo.	12mo.	Aged at 160F 1mo.	3mo.	12mo.	Cycled 10X to -95 F	Thermal Expans. Coef. $10^{-6}/°C$
Dow H	30-1,2,3	as cast	(as received)	F87								
	30-19,20,21	stress relieve	500F, 4 hrs., A.C.	E57	-20	-20	-25*	-20	-20	-15*	-10	25.2
		solutionize	750F, 8 hrs., A.C.									
	30-13,14,15	age	375F, 18 hrs., A.C.	E71	-15	-15	-15*	-20	-20	-20*	0	25.0
	30-16,17,18		500F, 4 hrs., A.C.	E75	-10	-20	-25*	-25	-25	-25*	-10	25.1
Dow O-1		wrought	(as received)									
	32-24,25,26	stress relieve	400F, 4hrs., A.C.	E74	-20	-25	-25*	- 5	+15	+20*	+10	24.0
		solutionize	750F, 4hrs., A.C.									
	32-18,19,20	age	350F, 20 hrs., A.C.	E81-84	-15	-15	-10*	-15	-15	-10*	+10	
	32-21,22,23		500F, 4 hrs., A.C.	E81-84	-15	-15	-20*	-20	-25	-25*	0	24.1
Dow M		extruded	(as received)									
	33-16,17,18	stress relieve	500F, 1/4 hr., A.C.-(R)	E36	- 3	-10	-10*	+ 5	+10	+10*	-10	24.2
Dow J-1		wrought	(as received)									
	34-10,11,12	stress relieve	500F, 1/4 hr., A.C.	E58	-10	-20	-20*	-18	-15	-15*	- 5	25.0
		cast	(as received)									
Dow C	160-7,8,9	stress relieve	500F, 4 hrs., A.C.	E74	- 5	-10	-15*	-15	-20	-20*	- 5	
		solutionize	750F, 20hrs., A.C.									
	160-1,2,3	age	420F, 14 hrs., A.C.	E5x	-10	-10	-15*	-40	-40	-40*	-15	24.4
	160-4,5,6		500F, 4 hrs., A.C.	E49	-10	-15	-20*	-15	-15	-10*	- 5	24.4
Dow AZ		cast	(as received)									
91C	170-1,2,3	stress relieve	400F, 4 hrs., A.C.	E54	-20	-30	-40*	-30	-30	-30*	-10	24.3
Dow		extruded	(as received)									
FS-1	171-1,2,3	stress relieve	500F, 1/4 hr., A.C.	E54	- 5	- 5	-10*	-10	-10	-15*	0	24.7

* 6 months of aging

(R) - reccommended treatment

A.C. - air cool

TABLE A-8. DIMENSIONAL STABILITY OF TITANIUM ALLOYS

Alloy	Spec. No.	Treatment		Rock-well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: 1mo.	Aged at 70F: 3mo.	Aged at 70F: 12mo.	Aged at 160F: 1mo.	Aged at 160F: 3mo.	Aged at 160F: 12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/°C$
Ti 75A	132-1,2,3	hot rolled	(as received)	B90	-10	-15	-	-20	-25	-	+10	
	132-10,11,12	stress relieve	400F, 1 hr., A.C.	B93	0	0	- 5	0	0	+ 5	+20	
	132-4,5,6		600F, 1hr., A.C.	B90	0	- 5	-	0	0	-	+15	8.6
	132-7,8,9		1000F, 1hr., A.C.	B96	+ 5	-	-	+ 5	-	-	+30	
Ti 150A	139-1,2,3	normalize	1550F, 1/2 hr., A.C.	C36	- 5	- 5	-	-10	-10	-	- 5	
	139-4,5,6	harden	1550F, 1/2 hr., O.Q.	C52	0	0	-	-15	-30	-	- 5	8.2
	139-10,11,12	stress relieve	350F, 4hrs., A.C.	C53	0	0	0	- 5	-10	-15	0	
	139-7,8,9		950F, 1hr., A.C.-(R)	C53	0	0	0	0	0	0	- 5	8.2
92Ti-5Cr-3Al	118-4,5,6	cold drawn	(as received)	C31	0	0	0*	+ 5	+ 5	+ 5*	- 5	
	1,2,3	anneal	1300F, 3 hrs., F.C.	C34	-10	-15	-	-10	-15	-	-15	
	7,8,9	stabilize	300F, 1hr., A.C.-(R)	C34	-10	-10	-10*	0	0	0*	- 5	8.6

* 6 months of aging

(R) - recommended treatment

A.C. - air cool

O.Q. - oil quench

F.C. - furnace cool

TABLE A-9. DIMENSIONAL STABILITY OF MISCELLANEOUS ALLOYS

Alloy	Spec. No.	Treatment		Rock-well Hard-ness	Microinch per Inch Length Change in Time and Cyclic Stability Tests: 1mo.	Aged at 70F: 3mo.	Aged at 70F: 12mo.	Aged at 160F: 1mo.	Aged at 160F: 3mo.	Aged at 160F: 12mo.	Cycled 10X to -95F	Thermal Expans. Coef. $10^{-6}/°C$
Gray Cast Iron	48-1,2,3	as cast	(as received)	B92	-15	-10	+ 5	- 5	- 5	-10	-20	10.3
Minovar Cast Iron	49-1,2,3	as cast	(as received)	B80	0	+ 5	+20	+25	+25	+30*	- 5	4.2
Kennametal K6M	70-1,2,3	sintered	(as received)	-	0	- 5	-	0	- 5	-	- 5	4.4
Kennametal KM	69-1,2,3	sintered	(as received)	-	0	- 5	-	0	0	-	- 5	4.8
Kennametal K12	71-1,2,3	sintered	(as received)	-	0	0	-	0	0	-	+ 5	4.2
Heavy Met	178-1,2,3	sintered	(as received)	C25	- 5	- 5	- 5*	-10	-10	-10*	- 5	6.0
Nitrided	14-1	nitrided	975F, 48 hrs., F.C.	54**	-10	-10	-15	-10	-10	-10*	-10	12.3
Nitralloy 135 mod.	14-2	stress relieve	1000F, 1hr., A.C.-(R)	54**	0	0	0	0	0	0	- 5	12.1

* 6 months of aging

** case hardness 15N scale

(R)- recommended treatment

TABLE A-10. RECOMMENDED HEAT TREATMENT FOR OBTAINING HIGH DIMENSIONAL STABILITY IN SELECTED ALLOYS

Alloy	Initial Condition	Desired Condition	Heat Treatment	Rockwell Hardness	Thermal Expansion Coef. $10^{-6}/°C$	Elastic Modulus 10^6 psi	Elastic Limit 10^3 psi
1112 steel	cold drawn	stress relieved	800F, 1 hr., A.C.	B95	11.8	28.5	76.
			or 1200F, 1 hr., A.C.	B77	11.8	28.4	63.0
1045 steel	cold drawn	stress relieved	1200F, 1 hr., F.C.	B92	-	-	-
		annealed	a) 1550F, 1/2 hr., F.C.				
			b) 300F, 1 hr., A.C.	B90	11.2	-	-
1144 steel	hot rolled	annealed	1550F, 1/2 hr., F.C.	B85	-	-	-
		hardened and	a) 1550F, 1/2 hr., O.Q.				
		tempered	b) 1100F, 1 hr., W.Q.	C23	11.1	-	-
4140 steel	hot rolled	annealed	1550F, 1/2 hr., F.C.	B95	11.4	-	-
		hardened and	a) 1550F, 1/2 hr., O.Q.				
		tempered	b) 1000F, 2 hrs., A.C.	C38	-	-	-
10100 steel	annealed	hardened and	a) 1450F, 1/2 hr., W.Q.				
		tempered*	b) 350F, 1 hr., A.C.	C64	11.0	-	-
Manganese Die Steel	annealed	hardened and	a) 1450F, 1/2 hr., O.Q.				
		tempered*	b) 300F, 1 hr., A.C.	C65	11.9	-	-
Tungsten Die steel	annealed	hardened and	a) 1600F, 1/2 hr., O.Q.				
		tempered*	b) 300F, 1 hr., A.C.	C65	11.6	-	-
52100 steel	annealed	hardened and	a) 1550F, 1/2 hr., O.Q.		-		
		tempered*	b) 250F, 10 hrs., A.C.	C65		-	-
			or 400F, 1 hr., A.C.	C62	11.9	-	-
High C High Cr Die steel	annealed	hardened and	a) 1850F, 1/2 hr., A.C.				
		tempered*	b) 300F, 2 hrs., A.C.	C63	10.3	-	-
			or 500F, 2 hrs., A.C.	C61	-	-	-
		hardened and	a) 1900F, 1/2 hr., A.C.				
		tempered*	b) -320F, 1 hr., A.H.				
			c) 950F, 1 hr., O.Q.				
			d) Repeat b) and c) four times				
			e) 450F, 1 hr., A.C.	C60	10.2	-	-
M-2 High Speed steel	annealed	hardened and tempered*	a) 2220F, 3 min., O.Q.				
			b) 1050F, 2 1/2 hrs., O.Q.				
			c) repeat b) three times				
			d) 900F, 1 hr., A.C.	C65	-	-	-
303 Stainless steel	cold drawn	quench annealed and stress relieved	a) 1950F, 1/2 hr., W.Q.				
			b) 600F, 1 hr., A.C.				
			c) 200F, 20 hrs., A.C.	B82	16.1	27.9	10.0
310 Stainless steel		quench-annealed and stress relieved	a) 1950F, 1/2 hr., W.Q.				
			b) 750F, 1 hr., A.C.	B84	14.6	-	-
410 Stainless steel		hardened and tempered	a) 1800F, 1/2 hr., O.Q.				
			b) 450F, 1 hr., A.C.	C46	-	-	-
			or 600F, 1 hr., A.C.	C41	10.2	31.4	10.8
440C stainless Steel	annealed	hardened and tempered	a) 1900F, 1/2 hr., O.Q.				
			b) 500F, 1 hr., A.C.	C61	10.2	-	-
Z-Nickel	cold drawn	age hardened	1060F, 8 hrs., F.C.				
			to 900F, A.C.	C40	12.4	32.1	114
Inconel	cold drawn	annealed	a) 1700F, 1 hr., F.C.				
			b) 200F, 24 hrs., A.C.	B71-79	12.7	30.1	15.0
K-Monel	cold drawn	age hardened	1000F, 9 hrs., F.C.				
			to 900F, A.C.	C37	13.4	26.2	110
Hastelloy B	cast	quench-annealed and stress relieved	a) 2100F, 1 hr., W.Q.				
			b) 1950F, 1 hr., W.Q.				
			c) 600F, 1 hr., A.C.	B95	10.4	-	-
Regular Invar	cold drawn	stress relieved	a) 1200F, 1 hr., A.C.				
			b) 200F, 48 hrs., A.C.	-	-	-	-

TABLE A-10. (Continued)

Alloy	Initial Condition	Desired Condition	Heat Treatment	Rock-well Hard-ness	Thermal Expansion Coef. $10^{-6}/°C$	Elastic Modulus 10^6 psi	Elastic Limit 10^3 psi
Free Cut	cold drawn	stress relieved	a) 1200F, 1 hr., F.C.				
Invar			b) 200F, 20 hrs., A.C.	B90-96	1.5	22.0	47.5
	cold drawn	quench-annealed	a) 1525F, 1/2 hr., W.Q.				
			b) 1203F, 1 hr., A.C.				
			c) 200F, 48 hrs., A.C.	B79	-	-	-
Ni-Span-Hi	cold drawn	solutionized	a) 1800F, 1 1/4 hrs., W.Q.				
		and aged	b) 1250F, 20 hrs., A.C.	C39	15.5	-	-
Beryllium-	cold drawn	solutionized	a) 1450F,7 hrs., W.Q.				
Copper		and aged	b) 600F, 2 hrs., A.C.	C37	16.9	19.0	58.5
2017 (17 S)	solutionized	solutionized	a) 940F,1/2 hr., W.Q.				
Aluminum alloy		and aged	b) 350F, 11 hrs., A.C.	B67	21.5	-	-
2024 (24 S)	solutionized	solutionized	a) 920F, 1/2 hr., W.Q.				
Aluminum alloy		and aged	b) 375F, 12 hrs., A.C.	B71	21.6	10.6	32.0
			or 400F, 2 hrs., A.C.	B72			
356 Aluminum	cast	solutionized	a) 1000F, 2 hrs., B.W.Q.				
alloy		and aged	b) 310F, 4 hrs., A.C.	B58	20.6	10.5	12.0
Low M Magnesium alloy	extruded	stress relieved	500F, 1/4 hr., A.C.	E36	24.2	-	-
150A Titanium alloy	hot rolled	normalized	1550F, 1/2 hr., A.C.	C38	-	-	-
		hardened and	a) 1550F, 1/2 hr., O.Q.				
		stress relieved	b) 600F, 1 hr., A.C.	C53	8.2	-	-
92Ti-6Cr-2Al	cold drawn	annealed	a) 1380F, 3 hrs., F.C.				
Titanium		and stress	b) 600F, 1 hr., A.C.	C34	8.6	-	-
alloy		relieved					
Nitralloy 135 mod.	nitrided	stress relieved	1000F, 1 hr., A.C.	15N54	12.1	-	-

*Treatment recommended if service temperature is maintained at about 70F.

A.C. - air cool
F.C. - furnace cool
O.Q. - oil quench

W.Q. - water quench
A.H. - air heat
B.W.Q. - boiling water quench

TABLE A-11. CHEMICAL COMPOSITION OF ALLOYS LISTED IN TABLES A-1 THROUGH A-10

I. Plain Carbon and Low Alloy Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Mo	Ni
175	1113	0.11	0.90	0.01	0.284	0.082	-	-	-
1	1020	0.10	0.46	0.01	0.043	0.015	-	-	-
16	X1020	0.17	0.86	0.08	0.404	0.011	-	-	-
6	1045	0.47	0.84	0.21	0.031	0.013	-	-	-
18	1144	0.41	1.38	0.09	0.288	0.023	-	-	-
8	4140	0.38	0.80	0.30	0.018	0.030	1.00	0.18	0.14
10	4340	0.40	0.80	0.33	0.014	0.030	0.80	0.26	1.07
3	1070	0.70	0.80	0.28	0.030	0.021	-	-	-

II. Tool Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Mo	V	W	Co
8	10100	1.00	0.30	0.35	0.014	0.014	-	-	-	-	-
K	10100	1.37	0.35	0.30	0.014	0.011	-	-	-	-	-
N	Manganese Die	0.94	1.17	0.31	0.010	0.030	0.50	-	0.24	0.52	-
G	Tungsten Die	1.24	0.30	0.20	0.007	0.008	0.76	0.23	0.20	1.50	-
176	51100	0.90	0.37	0.18	0.011	0.008	1.08	-	-	-	-
3	52100	1.08	0.30	0.30	0.010	0.083	1.34	-	0.21	-	-
T	52100	1.04	0.30	0.34	0.013	0.014	1.34	-	0.20	-	-
56	52100	1.00	0.36	0.28	0.014	0.010	1.30	0.08	-	-	-
68	1C-5Cr	1.00	0.61	0.17	0.018	0.014	5.31	1.13	0.27	-	-
F	High C, High Cr	1.54	0.30	0.40	0.007	0.015	12.0	0.80	0.77	-	0.40
64	High C, High Cr	1.00	0.33	0.38	0.010	0.015	11.86	0.70	0.25	-	-
B	M-2 High Speed	0.70	0.37	0.34	0.010	0.030	4.10	4.80	1.82	5.75	-

III. Stainless Steels

No.	Alloy	C	Mn	Si	S	P	Cr	Ni
15	302	0.08	0.71	0.51	0.013	0.030	18.30	8.40
7	303	0.13	0.84	0.36	0.300	0.036	17.86	9.00
28	310	0.10	1.07	0.30	0.030	0.018	24.10	18.74
24	410	0.13	0.46	0.47	0.013	0.018	13.86	-
20	440C	1.06	0.20	0.47	0.006	0.016	17.18	-

IV. Nickel Alloys

No.	Alloy	C	Mn	Si	S	P	Ni	Fe	Cr	Cu	Al	Ti
56	A-Nickel	0.08	0.21	0.09	0.006	-	99.52	0.14	-	0.05	-	-
54	Z-Nickel	0.17	0.27	0.05	0.005	-	94.14	0.15	-	0.02	4.30	0.30
173	Inconel	0.06	0.30	0.20	0.007	0.008	73.13	8.14	15.84	0.16		
57	Inconel	0.07	0.27	0.28	0.007	-	77.82	7.13	14.30	0.13	-	-
188	Inconel	0.08	0.20	0.10	0.007	-	76.64	7.41	15.63	0.10	-	-
						Cb						
80	Inconel X	0.04	0.40	0.36	0.007	0.90	73.40	6.40	14.80	0.02	0.77	2.84
80	Monel	0.10	1.00	0.12	0.008	-	66.23	1.30	-	30.28	-	-
56	K-Monel	0.14	0.54	0.15	0.006	-	66.15	0.90	-	28.94	2.10	0.40
										V	Mo	
170	Hastelloy B	0.04	0.41	0.36	-	-	66.70	5.87	0.36	0.42	26.80	-
60	Ni-Span-Lo 45	0.02	0.53	0.30	0.007	-	44.80	51.05	0.31	0.05	0.05	2.11
77	42Ni-58Fe	0.08	0.53	0.21	0.008	0.062	40.07	bal.	-	-	-	-
61	Ni-Span C	0.04	0.37	0.86	0.007	-	41.80	48.11	5.61	0.05	0.61	2.16
51	Reg. Invar	0.07	0.13	0.30	0.018	0.010	36.00	bal.	-	-	-	-
58	Reg. Invar	0.10	0.18	0.28	0.013	0.008	36.13	bal.	-	-	-	-
									Mo	Se		
52	Free Cut Invar	0.07	0.80	0.23	0.006	0.008	35.37	bal.	0.05	0.16	-	0.44
									Mo	Se		
66	Free Cut Invar	0.06	0.06	0.24	0.015	0.006	36.37	bal.	0.80	0.18	-	0.40
										Co		
9	Super Nilvar	0.08	0.15	0.13	0.015	0.008	31.30	bal.	-	5.37	-	-
76	32Ni-68Fe	0.10	0.76	0.27	0.008	0.008	33.54	bal.	-	-	-	-
62	Ni-Span-Hi	0.04	0.36	0.30	0.007	-	36.82	56.30	3.05	0.04	0.72	2.23

TABLE A-11. (Continued)

V. Copper Alloys

No.	Alloy	Cu	Sn	Zn	Pb	Fe	P	Ni	Be	Al
30	85-5-5-5	85.46	5.23	4.40	4.83	0.06	0.04	Tr	-	-
31	Beryl. Copper	97.04	-	-	-	0.0[illegible]	-	0.22	2.06	-
67	Beryl. Copper	97.01	-	-	-	0.08	0.06	0.03	1.92	Tr
41	70Cu-30Zn	68.47	Tr	31.53	Tr	Tr	-	-	-	Tr
43	Alum. Bronze	90.41	-	-	-	0.76	-	-	-	8.83
										Mn
66	Nickel Silver	65.96	-	16.04	-	-	<0.02	17.92	-	0.07

VI. Aluminum Alloys

No.	Alloy	Al	Si	Fe	Cu	Mn	Cr	Zn	Mg	Ti
143	2017 (17 S)	bal.								
21	2024 (24 S)	bal.	0.14	0.32	4.41	0.73	-	-	1.55	-
140	40E	bal	-	-	-	-	0.5*	5.5*	0.6*	0.2*
141	40E	bal.	-	-	-	-	0.5*	5.5*	2.3*	0.2*
26	4043 (43 S)	bal.	5.54	0.22	0.015	0.01	-	0.02	0.01	0.10
18	6061 (61 S)	bal.	0.58	0.23	0.24	0.06	0.27	-	1.10	-
19	7075 (75 S)	bal.	0.18	0.31	1.63	0.08	0.25	5.62	2.50	-
27	195	bal.	1.00	0.80	4.56	0.06	-	0.03	0.01	0.00
28	356	bal.	7.26	0.31	0.03	0.08	-	0.02	0.35	0.13
152	Apex Ternalloy	bal.	-	-	-	-	-	3.7*	1.8*	-

VII. Magnesium Alloys

No.	Alloy	Mg	Al	Zn	Mn	Si	Ni	Cu
30	Dow H	bal.	6.0*	3.0*	0.20(min)*	-	-	-
32	Dow O-1	bal.	8.5*	0.5*	0.15*	-	-	-
33	Dow M	bal.	-	-	1.50*	-	-	-
34	Dow J-1	bal.	6.5*	1.0*	0.20*	-	-	
169	Dow C	bal.	9.0	2.1	0.26	0.06	0.001	0.01
170	Dow AZ 91C	bal.	8.8	0.68	0.22	0.024	0.002	0.01
171	Dow FS-1	bal.	3.0*	1.0*	0.3*	-	-	-

VIII. Titanium Alloys

No.	Alloys	Ti	Al	Cr	Fe	N
132	Ti 75A	bal.	-	-	0.10* max.	0.02*
130	Ti 150A	bal.	-	2.8*	1.3*	0.08*
118	92Ti-5Cr-3Al	bal	3*	5*	-	-

IX. Miscellaneous Alloys

No.	Alloy									
		T.C.	Mn	Si	P	S	Ni	Cr	Cu	Mo
66	Grey Cast Iron	3.07	0.67	1.70	0.106	0.087	0.01	-	-	0.44
69	Ni-resist Cast Iron	3.16	0.61	1.90	0.010	0.007	34.0	0.13	0.06	-
		W	Ti	C	Co					
70	K5H Kennametal	67.5*	17.6*	6.0*	11*					
69	KM Kennametal	64*	16.7*	6.3*	6*					
71	K12 Kennametal	70.3*	17.6*	-	12*					
		W	Cu	Ni						
178	Heavy-Met	70-90*	2-30*	1-10*						
		C	Mn	Si	P	S	Cr	Mo	Al	
16	Nitralloy 135 mod.	0.41	0.61	0.30	0.016	0.017	1.50	0.34	1.10	

*Nominal Composition

Data From R-137, "The Properties of Metals and Alloys of Particular Interest in Precision Instrument Construction;

Compilation of data from various handbooks and other sources, by L. M. Schetky, January, 1957. Instrumentation Laboratory, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

The compilations in this report were taken from various published sources. The data on elastic limits and dimensional stability were taken from Report R-95(6), although in some cases differences in results or treatments can be noted. The units for the various parameters included are given as follows:

Density	Grams per cubic centimeter
Thermal Conductivity	Calories per square centimeter per centimeter per degree centigrade per second
Resistivity	Microhm-centimeter
Specific Heat	Calories per gram
Magnetic Properties	Either indicates permeability or whether material is or is not magnetic
Linear Coefficient of Expansion	Inch per inch per degree centigrade
Hardness	Rockwell scale as indicated or Brinell scale as indicated
UTS (Ultimate Tensile Strength)	1000 pounds per square inch
YP (0.2 Per Cent Offset Yield Strength)	Stress in 1000 pounds per square inch to produce 0.2 per cent offset
Elongation (in 2 in.)	Per cent
Modulus of Elasticity	1,000,000 pounds per square inch
Elastic Limit	1000 pounds per square inch
Elastic Limit/Density	(Pounds per square inch per gram per cubic centimeter) x 10^{-3}
Modulus of Elasticity/Density	(Pounds per square inch per gram per cubic centimeter) x 10^{-6}

The data for dimensional stability are presented in abbreviated form to show (1) the exposure condition: RT, 160, and cycle, meaning, respectively, exposure at 70 F, 160 F, or cycled ten times between -100 F and +200 F (note difference in cyclic exposure from that reported in R-95), (2) the dimensional change in microinches, and (3) the exposure time in months or years.

TABLE A-12. PROPERTIES OF METALS AND ALLOYS OF PARTICULAR INTEREST IN PRECISION INSTRUMENT CONSTRUCTION

4140 STEEL

Recommended Use

RT - 10 - 1 yr
160 - 5 - 1 yr
Cycle - 5

A deep hardening, hard, tough steel. May be copper brazed and hardened without excessive distortion.

Heat Treatment for:

Maximum dimensional stability

Procedure:

Initial condition: hot rolled
Anneal 1550°F, 1/2 hr, furnace cool, 1550°F, 1/2 hr, oil quench
1000°F, 2 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	7.85	Hardness	23C
Thermal conductivity	0.102	UTS	165
Resistivity	22.5	YP (0.2% offset)	140
Specific heat	0.114	Elongation (2 in.)	18
Magnetic properties	yes	Modulus of elasticity	29
Coefficient of expansion	11.1	Elastic limit	~100
		Elastic limit/dens.	12.7
		Mod./dens.	3.7

1095 STEEL

Recommended Use

RT - 10 - 1 yr

A water hardening steel where high hardness, high strength is desired. Stability fair

Heat Treatment for

Maximum dimensional stability, and high hardness.

Procedure

Initial condition: annealed stock
1450°F, 1/2 hr, water quench
350°F, 1 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.85	Hardness	64C
Thermal conductivity	0.107	UTS	~[illegible]
Resistivity	25.3	YP (0.2% offset)	~250
Specific heat	0.116	Elongation (2 in.)	~10
Magnetic properties	yes	Modulus of elasticity	~29
Coefficient of expansion	11.0	Elastic limit	~90
		Elastic limit/dens.	11.5
		Mod./dens.	3.71

NITRALLOY - 135 MODIFIED

Recommended Use

RT - 0 - 1 yr
160 - 0 - 1 yr
Cycle - 5

For use where extreme wear resistance is desired. Excellent stability.

Heat Treatment for

Maximum dimensional stability consistent with a case hardened, tough core structure

Procedure

Initial condition: annealed
Stress relieved 1000°F, air cool

Physical Properties		Mechanical Properties	
Density	7.84	Hardness	64C (case)
Thermal conductivity	0.124	UTS	206
Resistivity	27-29	YP (0.2% offset)	181.5
Specific heat	0.11-0.12	Elongation (2 in.)	15.2
Magnetic properties	yes	Modulus of elasticity	29-30
Coefficient of expansion	12.1	Elastic limit	~120
		Elastic limit/dens.	15.3
		Mod./dens.	3.82

TABLE A-12. (Continued)

1144 STEEL

Recommended Use: RT – 0 – 6 mo; 100 – 0 – 3 mo; Cycle – 4	Free machining, hardenable plain carbon general purpose steel
Heat Treatment for:	Maximum dimensional stability with medium mechanical properties.
Procedure:	Initial condition: hot rolled; 1550°F, 1/2 hr, oil quench; 1100°F, 5 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	7.82	Hardness	23C
Thermal conductivity	0.121	UTS	100
Resistivity	15.9	YP (0.2% offset)	70
Specific heat	0.116	Elongation (2 in.)	16
Magnetic properties	yes	Modulus of elasticity	30
Coefficient of expansion	11.1	Elastic limit	~40
		Elastic limit/dens.	5.11
		Mod./dens.	3.84

SILICON STEEL #15

Recommended Use:	Motors, generators, transformers
Heat Treatment for:	Maximum magnetic properties
Procedure:	Anneal 1500°F, 1 hr, furnace cool

Physical Properties:		Mechanical Properties:	
Density	7.55	Hardness	75B
Thermal conductivity	0.056	UTS	61-79
Resistivity	61	YP (0.2% offset)	60-66
Specific heat	0.12	Elongation (2 in.)	4.3-7.8
Magnetic properties	μ = 3600 approx	Modulus of elasticity	~29
Coefficient of expansion	~11.5	Elastic limit	~50
		Elastic limit/dens.	6.62
		Mod./dens.	3.84

1045 STEEL

Recommended Use: RT – 0 – 3 mo; 100 – 5 – 3 mo; Cycle – 5	As a hardenable plain carbon steel
Heat Treatment for:	Maximum dimensional stability
Procedure:	Initial condition: cold drawn; 1550°F, 1/2 hr, furnace cool; 500°F, 1 hr, air cool

Physical Properties:		Mechanical Properties:*	
Density	7.85	Hardness	93B
Thermal conductivity	0.121	UTS	72
Resistivity	15.9	YP (0.2% offset)	70
Specific heat	0.116	Elongation (2 in.)	16
Magnetic properties	yes	Modulus of elasticity	30
Coefficient of expansion	11.2	Elastic limit	~17
		Elastic limit/dens.	2.16
		Mod./dens.	3.82

* Annealed properties, considerably higher in hardened condition.

1112 STEEL

Recommended Use: RT – 0 – 1 yr; 150 – 0 – 1 yr; Cycle – 4	A low carbon free machining steel of moderate strength and good stability
Heat Treatment for:	Maximum dimensional stability
Procedure:	Initial condition: cold rolled; Stress relief 800°F, 1 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	7.85	Hardness	77B
Thermal conductivity	0.124	UTS	87
Resistivity	12.6	YP (0.2% offset)	74
Specific heat	0.115	Elongation (2 in.)	17
Magnetic properties	yes	Modulus of elasticity	28.4
Coefficient of expansion	11.8	Elastic limit	63
		Elastic limit/dens.	8.03
		Mod./dens.	3.62

SILICON STEEL

Recommended Use: RT – 10	A magnetic steel, especially for transformers requiring low loss.
Heat Treatment for:	Maximum magnetic properties
Procedure:	Anneal 1500°F, 1 hr, furnace cool

Physical Properties:		Mechanical Properties:	
Density	7.55	Hardness	70B
Thermal conductivity	0.050	UTS	65-75
Resistivity	56	YP (0.2% offset)	56-62
Specific heat	0.12	Elongation (2 in.)	7.3-6.3
Magnetic properties	μ = 1000 approx	Modulus of elasticity	~29
Coefficient of expansion	~11.5	Elastic limit	~45
		Elastic limit/dens.	5.95
		Mod./dens.	3.84

1020 STEEL

Recommended Use:	General purpose steel. Not particularly stable.
Heat Treatment for:	None
Procedure:	Cold rolled. If annealed use 1650°F, 1 hr.

Physical Properties:		Mechanical Properties:	
Density	7.85	Hardness	80B
Thermal conductivity	0.122	UTS	75
Resistivity	15.9	YP (0.2% offset)	63.5
Specific heat	0.116	Elongation (2 in.)	30
Magnetic properties	μ = 2000 max	Modulus of elasticity	30.1
Coefficient of expansion	12.2	Elastic limit	~50
		Elastic limit/dens.	6.34
		Mod./dens.	3.84

TABLE A-12. (Continued)

52100 STEEL

Recommended Use

RT – 3 – 1 yr
150°F – 0 – 1 yr
Cycle – 3

Bearing use.

Heat Treatment for

Maximum dimensional stability with high strength and hardness

Procedure

Initial condition: annealed
1550°F, 1/2 hr, oil quench
400°F, 1 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.83	Hardness	61.5C
Thermal conductivity	0.108	UTS	~ 300
Resistivity	~ 22	YP (0.2% offset)	~ 250
Specific heat	0.122	Elongation (2 in.)	~ 10
Magnetic properties	yes	Modulus of elasticity	29.2
Coefficient of expansion	11.9	Elastic limit	89
		Elastic limit dens	11.4
		Mod. dens	3.73

DIE STEEL – Mn

Recommended Use

RT – 0 – 1 yr

Oil hardening for nondeforming characteristics. Where warpage in heat treatment is to be avoided

Heat Treatment for

Maximum dimensional stability

Procedure

Initial condition – annealed
1450°F, 1/2 hr, oil quench
300°F, 1 hr, air cool

Physical Properties		Mechanical Properties	
Density		Hardness	65C
Thermal conductivity		UTS	
Resistivity		YP (0.2% offset)	
Specific heat		Elongation (2 in.)	
Magnetic properties		Modulus of elasticity	
Coefficient of expansion	11.9	Elastic limit	
		Elastic limit dens	
		Mod. dens	

DIE STEEL – M2

Recommended Use

RT – 0 – 3 mo

General purpose high speed steel. Typical care required to minimizing distortion on heat treatment

Heat Treatment for

Maximum dimensional stability

Procedure: Initial condition annealed

a. 2220°F – 3 min oil quench
b. 1050°F – 2½ hr oil quench
c. Repeat b 3 times
d. 900°F 1 hr, air cool

Physical Properties		Mechanical Properties	
Density		Hardness	65C
Thermal conductivity		UTS	
Resistivity		YP (0.2% offset)	
Specific heat		Elongation (2 in.)	
Magnetic properties		Modulus of elasticity	
Coefficient of expansion	10.3	Elastic limit	
		Elastic limit dens	
		Mod. dens	

DIE STEEL – HIGH C, HIGH Cr

Recommended Use

*RT – 0 – 6 mo
160 – 10 – 6 mo
Cycle – 10

Used for die purposes requiring air hardening and extreme wear resistance

Heat Treatment for

Maximum dimensional stability with die properties

Procedure

Initial conditions – annealed
*1850°F, 1/2 hr, air cool
300°F, 2 hr, air cool
300°F, 2 hr, air cool

for minimum warpage

Physical Properties		Mechanical Properties	
Density		Hardness	63C (300°F), 61C (500°F)
Thermal conductivity		UTS	
Resistivity		YP (0.2% offset)	
Specific heat		Elongation (2 in.)	
Magnetic properties		Modulus of elasticity	
Coefficient of expansion	10.3	Elastic limit	
		Elastic limit dens	
		Mod. dens	

* Note: Oil quench gives better stability: 1800°F, 1/2 hr, oil quench
temper 300°F, 2 hr, air cool

DIE STEEL – TUNGSTEN

Recommended Use

RT – 0 – 1 yr

For high wear resistance, non-galling

Heat Treatment for

Maximum dimensional stability

Procedure

Initial condition – annealed
1400°F, 1/2 hr, oil quench
300°F, air cool

Physical Properties		Mechanical Properties	
Density		Hardness	65C
Thermal conductivity		UTS	
Resistivity		YP (0.2% offset)	
Specific heat		Elongation (2 in.)	
Magnetic properties		Modulus of elasticity	
Coefficient of expansion	11.6	Elastic limit	
		Elastic limit dens	
		Mod. dens	

STAINLESS STEEL 310

Recommended Use

RT – 5 – 1 yr
160 – 10 – 1 yr
Cycle – 20

Nonmagnetic in annealed or cold work state. High heat and corrosion resistance. Good general purpose stainless steel.

Heat Treatment for

Maximum dimensional stability

Procedure

Quench anneal, 1950°F, 1/2 hr
Water quench, stress relieve 750°F, 200°F, 20 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.98	[illegible]	[illegible]
Thermal conductivity	0.033	UTS	100
Resistivity	75	YP (0.2% offset)	45
Specific heat	0.12	Elongation (2 in.)	50
Magnetic properties	none	Modulus of elasticity	29
Coefficient of expansion	14.4	Elastic limit	30
		Elastic limit dens	3.81
		Mod. dens	3.68

TABLE A-12. (Continued)

STAINLESS STEEL 440C

Recommended Use:
RT – 10 – 6 mo — Hardenable stainless
160 – 5 – 6 mo — Highest hardness of the stainless steels.
Cycle – 5

Heat Treatment for:
Maximum dimensional stability

Procedure:
Initial condition: annealed
1900°F, 1/2 hr, oil quench
300°F, 1 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.75	Hardness	61C
Thermal conductivity	0.57	UTS	285,000
Resistivity	50	YP (0.2% offset)	275,000
Specific heat	0.11	Elongation (2 in.)	1
Magnetic properties	yes	Modulus of elasticity	29
Coefficient of expansion	10.2	Elastic limit	~190,000
		Elastic limit/dens.	24.5
		Mod./dens.	3.74

STAINLESS STEEL 303

Recommended Use:
RT – 0 – 6 mo — For corrosion resistance; nonmagnetic, though can be slightly magnetic
160 – 5 – 3 mo — upon cold work. Low yield and elastic limits.
Cycle – 5

Heat Treatment for:
Maximum dimensional stability

Procedure:
1950°F, 1/2 hr, water quench
Stress relief 600°F, 1 hr, air cool
300°F, 20 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.9	Hardness	B85
Thermal conductivity	0.050	UTS	90
Resistivity	60	YP (0.2% offset)	30
Specific heat	0.122	Elongation (2 in.)	50
Magnetic properties	none	Modulus of elasticity	28
Coefficient of expansion	16.1	Elastic limit	10.4
		Elastic limit/dens.	1.3
		Mod./dens.	3.65

STAINLESS STEEL 410

Recommended Use:
RT – 5 – 1 yr — General purpose chrome stainless.
160 – 10 – 1 yr — Hardenable by heat treatment. Corrosion and heat resistant.
Cycle – 5

Heat Treatment for:
Maximum dimensional stability

Procedure:
1800°F, 1/2 hr, oil quench
600°F, 1 hr, air cool (R_c 41)
or 650°F, 1 hr, air cool (R_c 40)

Physical Properties		Mechanical Properties	
Density	7.75	Hardness	41C
Thermal conductivity	0.059	UTS	195
Resistivity	56	YP (0.2% offset)	152
Specific heat	0.115	Elongation (2 in.)	15
Magnetic properties	yes	Modulus of elasticity	31.4
Coefficient of expansion	10.2	Elastic limit	108
		Elastic limit/dens.	14.0
		Mod./dens.	4.7

NICKEL

Recommended Use:
RT – 5 – 1 yr — As an alloying addition for electronic devices
As a protective coating for chemical or heat resistance

Heat Treatment for:
Normal properties

Procedure:
Anneal – 1500°F, 3 to 6 min, air cool
Stress relief 600°F for 1 hr
(Note: Reasonably stable in the as-received cold-drawn condition)

Physical Properties		Mechanical Properties	
Density	8.9	Hardness	76B
Thermal conductivity	0.21	UTS	85
Resistivity	6.84	YP (0.2% offset)	46
Specific heat	0.108	Elongation (2 in.)	30
Magnetic properties	μ < 5000	Modulus of elasticity	22
Coefficient of expansion	12.5	Elastic limit	4.5
		Elastic limit/dens.	0.505
		Mod./dens.	2.47

STAINLESS STEEL 303 (COLD DRAWN)

Recommended Use:
Higher strength to weight. Slight magnetic.
Better elastic limit than annealed 303.

Heat Treatment for:
Stress relief with minimum decrease in mechanical properties.

Procedure:
Cold drawn (approximately 50% red.)
Stress relieve furnace heat [illegible]°F, 1 hr, air cool
300°F, 20 hr, air cool

Physical Properties		Mechanical Properties	
Density	7.9	Hardness	B97
Thermal conductivity	0.050	UTS	215
Resistivity	60	YP (0.2% offset)	170
Specific heat	0.122	Elongation (2 in.)	9
Magnetic properties	slight	Modulus of elasticity	28
Coefficient of expansion	16.1	Elastic limit	41
		Elastic limit/dens.	5.20
		Mod./dens.	3.55

HASTELLOY B

Recommended Use:
RT – 0 – 1 yr — Very high strength, high corrosion resistance, excellent stability.
160 – 0 – 1 yr
Cycle – 0

Heat Treatment for:
Maximum dimensional stability

Procedure:
Quench anneal 2100°F, 1 hr, water quench
Quench anneal 1950°F, 1 hr, water quench
Stress relieve 600°F, 1 hr, air cool

Physical Properties		Mechanical Properties	
Density	9.34	Hardness	95B
Thermal conductivity	0.027	UTS	160-200
Resistivity	135	YP (0.2% offset)	120-150
Specific heat	0.091	Elongation (2 in.)	[illegible]
Magnetic properties	Poor, μ = 1	Modulus of elasticity	32.1
Coefficient of expansion	10.4	Elastic limit	114
		Elastic limit/dens.	12.3
		Mod./dens.	3.40

TABLE A-12. (Continued)

INCONEL

Recommended Use	
RT – 2 – 1 yr 150 – 0 – 1 yr Cycle – 5	For excellent high temperature oxidation resistance, high creep strength; good strength
Heat Treatment for	Maximum stability
Procedure	Initial condition: cold drawn 1700°F, 1 hr, furnace cool 200°F, 48 hr, air cool

Physical Properties		Mechanical Properties	
Density	8.51	Hardness	75-85B
Thermal conductivity	0.036	UTS	80–100
Resistivity	98.1	YP (0.2% offset)	25-50
Specific heat	0.109	Elongation (2 in.)	50-35
Magnetic properties	none	Modulus of elasticity	30.1
Coefficient of expansion	12.8	Elastic limit	15
		Elastic limit/dens.	1.76
		Mod./dens.	3.54

NI SPAN C

Recommended Use	
RT – 10 – 6 mo 160 – 15 – 6 mo Cycle – 30	High physical properties, age hardenable. Can replace Be Cu particularly where brazing is necessary. Zero T-coefficient of modulus.
Heat Treatment for	Optimum strength and zero T-coefficient of modulus of elasticity.
Procedure	Initial condition: cold drawn 1800°F, 1½ hr, water quench age 1250°F, 21 hr, air cool

Physical Properties		Mechanical Properties	
Density	8.15	Hardness	29C
Thermal conductivity	0.0302	UTS	100
Resistivity	79.7	YP (0.2% offset)	115
Specific heat	0.12	Elongation (2 in.)	18
Magnetic properties	yes	Modulus of elasticity	26.5*
Coefficient of expansion	7.2	Elastic limit	57.5
		Elastic limit/dens.	7.06
		Mod./dens.	3.29

* Note zero T-coefficient.

Z NICKEL

Recommended Use	
RT – 0 – 3 mo	High strength with good corrosion resistance, especially in large sections
Heat Treatment for	Maximum stability after cycling
Procedure	Initial condition: cold drawn 1000°F, 9 hr, furnace cool to 900°F, air cool Cycle – 100 to +200°F minimum 10 times

Physical Properties		Mechanical Properties	
Density	8.26	Hardness	40C
Thermal conductivity	0.04	UTS	160-200
Resistivity	43.1	YP (0.2% offset)	120-150
Specific heat	0.106	Elongation (2 in.)	30-15
Magnetic properties	none	Modulus of elasticity	32.1
Coefficient of expansion	12.4	Elastic limit	114
		Elastic limit/dens.	13.8
		Mod./dens.	3.80

GYROLLOY

Recommended Use	
No data*	Experimental alloy for use as gyro wheel. Elastic limit a function of heat treatment. Coefficient of linear expansion to match 52100.
Heat Treatment for	Maximum stability and elastic properties
Procedure	1600°F, 1hr/in., furnace cool

Physical Properties		Mechanical Properties	
Density	8.26	Hardness	
Thermal conductivity	not	UTS	
Resistivity	yet	YP (0.2% offset)	not yet
Specific heat	available	Elongation (2 in.)	available
Magnetic properties	none**	Modulus of elasticity	28
Coefficient of expansion	11.5-11.9	Elastic limit	20
		Elastic limit/dens.	2.42
		Mod./dens.	3.39

* Dimensional stability expected to be comparable to Invar

** Nonmagnetic at T slightly above room temperature.

HYPERNIK

Recommended Use	
No data	For magnetic circuits. Strain sensitive and low creep strength
Heat Treatment for	Maximum magnetic permeability
Procedure	1200°C, 20 hr furnace cool (Hydrogen atmosphere)

Physical Properties		Mechanical Properties	
Density	8.25	Hardness	50-60B
Thermal conductivity	0.03	UTS	65
Resistivity	45	YP (0.2% offset)	22
Specific heat	0.115	Elongation (2 in.)	20
Magnetic properties, max μ	=60,000 to 100,000	Modulus of elasticity	24
Coefficient of expansion	8.4	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	2.91

NI SPAN HI

Recommended Use	
RT – 5 – 6 mo. 160 – 10 – 6 mo. Cycle 10	For reasonably constant modulus and a specific coefficient of linear expansion. Good elastic limit.
Heat Treatment for	Maximum dimensional stability
Procedure	Initial condition: cold drawn 1800°F, 1¼ hr, water quench Age at 1250°F, 20 hr, air cool

Physical Properties		Mechanical Properties	
Density	8.1	Hardness	30C
Thermal conductivity	~0.02	UTS	140
Resistivity	~80	YP (0.2% offset)	90
Specific heat	~0.12	Elongation (2 in.)	20
Magnetic properties	yes	Modulus of elasticity	29
Coefficient of expansion	13.5	Elastic limit	47
		Elastic limit/dens.	5.8
		Mod./dens.	3.58

TABLE A-12. (Continued)

MUMETAL

Recommended Use

No data — For magnetic properties, high permeability. Has low creep strength, and is stress sensitive.

Heat Treatment for

Maximum magnetic permeability

Procedure

1175°C in hydrogen, 10 hr, slow cool.

Physical Properties		Mechanical Properties	
Density	8.58	Hardness	
Thermal conductivity		UTS	64
Resistivity	62	YP (0.2% offset)	30.3
Specific heat		Elongation (2 in.)	27
Magnetic properties	high μ	Modulus of elasticity	~ 30
Coefficient of expansion	12.5	Elastic limit	
		Elastic limit/dens	
		Mod/dens	~ 3.49

R MONEL

Recommended Use

No data — Same properties as Monel but with greater machinability, dimensional stability should be about the same.

Heat Treatment for

None

Procedure

Initial condition: cold drawn

Physical Properties		Mechanical Properties	
Density	8.34	Hardness	60-100B
Thermal conductivity	0.062	UTS	79-115
Resistivity	48.2	YP (0.2% offset)	30-100
Specific heat	0.127	Elongation (2 in.)	50-20
Magnetic properties	μ = 2000 to 10,000	Modulus of elasticity	26
Coefficient of expansion	14.0	Elastic limit	42
		Elastic limit/dens	4.75
		Mod/dens	2.94

FREE CUTTING INVAR

Recommended Use

RT – 10 – 6 mo — For low coefficient of linear expansion, good elastic limit and stability.
60 – 0 – 6 mo
Cycle – 10 (Stability based on heat treatment No. 2. Approximately same for heat treatment No. 1)

Heat Treatment for

Maximum stability

Procedure: Initial condition: cold drawn

1. 1200°F, 1 hr, furnace cool; 200°F, 20 hr
2. 1525°F, 1/2 hr, water quench; 1200°F, 1 hr, air cool; 200°F, 40 hr, air cool

Physical Properties		Mechanical Properties	
Density	8.15	Hardness	90B
Thermal conductivity	0.025	UTS	90
Resistivity	81	YP (0.2% offset)	70
Specific heat	0.125	Elongation (2 in.)	26
Magnetic properties	max μ 3000	Modulus of elasticity	22
Coefficient of expansion	2.0	Elastic limit	47.5
		Elastic limit/dens	5.85
		Mod/dens	2.71

Mechanical properties for heat treatment No. 1 (stress relief)

MONEL

Recommended Use

RT – 15 – 1 yr — Strength coupled with excellent resistance to corrosion.

Heat Treatment for

None – used in cold drawn condition for maximum strength.

Procedure

Initial condition: cold drawn

Physical Properties		Mechanical Properties	
Density	8.84	Hardness	85B-23C
Thermal conductivity	0.062	UTS	85-125
Resistivity	48.2	YP (0.2% offset)	55-120
Specific heat	0.127	Elongation (2 in.)	35-10
Magnetic properties	μ = 2000 to 10,000	Modulus of elasticity	26
Coefficient of expansion	14	Elastic limit	54
		Elastic limit/dens	6.1
		Mod/dens	2.94

K MONEL

Recommended Use

RT – 5 – 3 mo. — Good elastic properties and age hardenable. Good corrosion resistance.
160 – 5 – 3 mo.
Cycle – 0

Heat Treatment for

Maximum dimensional stability

Procedure

Initial condition: cold drawn
1. 1000°F for 9 hr, furnace cool to 900°F, air cool

Physical Properties		Mechanical Properties	
Density	8.47	Hardness	[illegible]-33C
Thermal conductivity	0.045	UTS	140-170
Resistivity	58.3	YP (0.2% offset)	100-130
Specific heat	0.127	Elongation (2 in.)	30-[illegible]
Magnetic properties	none	Modulus of elasticity	26.2
Coefficient of expansion	13.4	Elastic limit	110
		Elastic limit/dens	13.0
		Mod/dens	3.33

COPPER (ELECTROLYTIC TOUGH PITCH)

Recommended Use

High conductivity use

Heat Treatment for

None

Procedure

As received

Physical Properties		Mechanical Properties	
Density	8.94	Hardness	40F
Thermal conductivity	0.934	UTS	32
Resistivity	1.71	YP (0.2% offset)	10
Specific heat	0.92	Elongation (2 in.)	45
Magnetic properties	none	Modulus of elasticity	17
Coefficient of expansion	17.[illegible]	Elastic limit	
		Elastic limit/dens	
		Mod/dens	1.9

TABLE A-12. (Continued)

BERYLLIUM COPPER NO. 25

Recommended Use:
RT – 0 – 3 mo
160 – 5 – 3 mo
Cycle – 5

High strength; high elastic limit; not notch sensitive, easy to heat treat with minimum distortion.

Heat Treatment for:

* Maximum dimensional stability and maximum physical properties

Procedure:

Initial condition: cold drawn
*1450°F, 2 hr, water quench
600°F, 2 hr, air cool

Physical Properties		Mechanical Properties	
Density	8.23	Hardness	37C
Thermal conductivity	0.25	UTS	175
Resistivity	6.8-9.3	YP (0.2% offset)	80 (0.01%)
Specific heat	0.1	Elongation (2 in.)	5
Magnetic properties	none	Modulus of elasticity	19
Coefficient of expansion	15.9	Elastic limit	58.5
		Elastic limit/dens.	7.11
		Mod./dens.	2.3

* Note: a slightly better elastic limit is obtained by 625°F for 2 hr. This has not yet been checked for stability.

PHOSPHOR BRONZE 5%

Recommended Use

For springs, bellows, lock washers, readily formed cold; general purpose spring material

Heat Treatment for

Procedure

Cold rolled

Physical Properties		Mechanical Properties	
Density	8.86	Hardness	90B
Thermal conductivity	0.19	UTS	92
Resistivity	9.6	YP (0.2% offset)	82
Specific heat	0.09	Elongation (2 in.)	5.5
Magnetic properties	none	Modulus of elasticity	16
Coefficient of expansion	17.8	Elastic limit	72
		Elastic limit dens.	8.13
		Mod. dens.	1.81

BRASS 60-40

Recommended Use

General purpose for fixtures and noncritical parts. Good machining

Heat Treatment for

None

Procedure

Initial condition: 1/2 hard

Physical Properties		Mechanical Properties	
Density	8.39	Hardness	80B
Thermal conductivity	0.29	UTS	70
Resistivity	6.2	YP (0.2% offset)	50 (0.1%)
Specific heat	0.09	Elongation (2 in.)	5
Magnetic properties	none	Modulus of elasticity	15
Coefficient of expansion	20.8	Elastic limit	24
		Elastic limit dens.	2.86
		Mod. dens.	1.79

ALUMINUM 356

Recommended Use
RT – 0 – 3 mo
160 – 0 – 3 mo
Cycle – 5

Best casting alloy for high strength dimensionally stable parts.

Heat Treatment for

Maximum dimensional stability

Procedure

Initial condition: as cast
1000°F, 2 hr, boiling water quench
310°F, 4 hr, air cool

Physical Properties		Mechanical Properties	
Density	2.68	Hardness	59B
Thermal conductivity	0.36	UTS	33
Resistivity	4.42	YP (0.2% offset)	24
Specific heat	0.23	Elongation (2 in.)	4
Magnetic properties	none	Modulus of elasticity	10.5
Coefficient of expansion	20.8	Elastic limit	12
		Elastic limit dens.	3.92
		Mod./dens.	4.47

BRASS 70-30

Recommended Use
RT – 30 – 1 yr
160 – 5 – 1 yr
Cycle – 30

Deep drawing characteristics, not stable

Heat Treatment for

None

Procedure

Initial condition: hard (30% cold reduction)

Physical Properties		Mechanical Properties	
Density	8.53	Hardness	61B
Thermal conductivity	0.29	UTS	60
Resistivity	6.2	YP (0.2% offset)	49 (0.1%)
Specific heat	0.09	Elongation (2 in.)	19.5
Magnetic properties	none	Modulus of elasticity	15
Coefficient of expansion	19.4	Elastic limit	27
		Elastic limit dens.	3.17
		Mod. dens.	1.76

ALUMINUM 6061 (WROUGHT)

Recommended Use
RT – 15 – 3 mo
160 – 5 – 3 mo
Cycle – 20

Very good corrosion resistance, good strength and workability, takes anodizing well.

Heat Treatment for

Optimum mechanical properties

Procedure

970°F, 1/2 hr, water quench
350°F, 6 hr, air cool

Physical Properties		Mechanical Properties	
Density	2.7	Hardness	35B
Thermal conductivity	0.37	UTS	45
Resistivity	4.3	YP (0.2% offset)	40
Specific heat	0.23	Elongation (2 in.)	15
Magnetic properties	none	Modulus of elasticity	10
Coefficient of expansion	20.0	Elastic limit	~12
		Elastic limit dens.	4.44
		Mod. dens.	3.7

TABLE A-12. (Continued)

ALUMINUM 6061 (WROUGHT)

Recommended Use:	Good forgeability; good corrosion resistance; may be readily anodized.
Heat Treatment for:	Maximum mechanical properties.
Procedure:	985°F, 1 hr, water quench 350°F, 8-12 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	2.69	Hardness	920
Thermal conductivity	0.41	UTS	47
Resistivity	3.60	YP (0.2% offset)	40
Specific heat	0.23	Elongation (2 in.)	20
Magnetic properties	none	Modulus of elasticity	10.2
Coefficient of expansion	23.5	Elastic limit	~20
		Elastic limit/dens.	7.39
		Mod./dens.	3.79

ALUMINUM 2024

Recommended Use: RT – 5 – 1 yr 350 – 16 – 1 yr Cycle – 5	Where strengths higher than 2017 are required.
Heat Treatment for:	Maximum dimensional stability
Procedure:	920°F, 1/2 hr, water quench 375°F, 12 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	2.77	Hardness	600
Thermal conductivity	0.29	UTS	68
Resistivity	5.75	YP (0.2% offset)	46
Specific heat	0.23	Elongation (2 in.)	22
Magnetic properties	none	Modulus of elasticity	10.4
Coefficient of expansion	21.6	Elastic limit	22
		Elastic limit/dens.	7.94
		Mod./dens.	3.75

ALUMINUM 7075 (WROUGHT)

Recommended Use: RT – approx 20 – 1 yr	Highest strength of the aluminum alloys. Not particularly stable.
Heat Treatment for:	Maximum mechanical properties
Procedure:	870°F, 1 hr, water quench 250°F, 24 to 28 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	2.8	Hardness	680
Thermal conductivity	0.29	UTS	80
Resistivity	5.75	YP (0.2% offset)	80
Specific heat	0.23	Elongation (2 in.)	10
Magnetic properties	none	Modulus of elasticity	10.4
Coefficient of expansion	23.6	Elastic limit	~40
		Elastic limit/dens.	14.3
		Mod./dens.	3.72

MAGNESIUM – B

Recommended Use: RT – 10 – 6 mo. 160 – 10 – 6 mo. Cycle – 10	Wrought; may be sand cast. For light structures of moderate strength.
Heat Treatment for:	Maximum dimensional stability
Procedure:	As received – extruded Stress relieve – 500°F, 1/4 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	1.76	Hardness	E 56
Thermal conductivity	0.30	UTS	38
Resistivity	5.0	YP (0.2% offset)	28
Specific heat	0.2[illegible]	Elongation (2 in.)	10
Magnetic properties	none	Modulus of elasticity	6.5
Coefficient of expansion	26.3	Elastic limit	~9
		Elastic limit/dens.	5.1
		Mod./dens.	3.7

ALUMINUM 2017

Recommended Use: RT – 5 – 3 mo 300 – 5 – 3 mo Cycle – 0	Relatively one of the higher strength alloys; good forming; good resistance to corrosion. Obtainable in larger sizes than 2024.
Heat Treatment for:	Maximum dimensional stability
Procedure:	940°F, 1/2 hr, water quench 350°F, 11 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	2.79	Hardness	660
Thermal conductivity	0.29	UTS	62
Resistivity	5.75	YP (0.2% offset)	40
Specific heat	0.23	Elongation (2 in.)	22
Magnetic properties	none	Modulus of elasticity	10.5
Coefficient of expansion	23.5	Elastic limit	30
		Elastic limit/dens.	10.8
		Mod./dens.	3.75

MAGNESIUM – [illegible]

Recommended Use:	No dimensional change
Heat Treatment for:	Maximum mechanical properties
Procedure:	As received – cast 730°F, 20 hr, air blast cool 500°F, 4 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	1.8	Hardness	480
Thermal conductivity	0.17	UTS	40
Resistivity	14	YP (0.2% offset)	22
Specific heat	0.25	Elongation (2 in.)	5
Magnetic properties	none	Modulus of elasticity	6.5
Coefficient of expansion	26	Elastic limit	~12
		Elastic limit/dens.	6.7
		Mod./dens.	3.6

TABLE A-12. (Continued)

DUCTILE TITANIUM (PURE)

Recommended Use: Strength to weight typical of the 70A alloy. Good corrosion resistance. Readily joined.

Heat Treatment for: Stress relief

Procedure: Annealed 1000°F

Physical Properties:		Mechanical Properties:	
Density	4.5	Hardness	50-59A
Thermal conductivity	0.036	UTS	90
Resistivity	55	YP (0.2% offset)	80
Specific heat	0.126	Elongation (2 in.)	20
Magnetic properties	none	Modulus of elasticity	16.0
Coefficient of expansion	8.8	Elastic limit	52
		Elastic limit/dens.	11.6
		Mod./dens.	3.55

TITANIUM 3Al 5Cr

Recommended Use:
RT – 30 – 6 mo
160 – 0 – 6 mo
Cycle – 5

For strength to weight ratio material. Good corrosion resistance. Hardenable by cold work.

Heat Treatment for: Maximum stability

Procedure:
Initial condition: cold drawn
Anneal 1300°F, 3 hr, furnace cool
Stabilize 500°F, 1 hr, air cool

Physical Properties:		Mechanical Properties:	
Dens.	4.59	Hardness	34C
Thermal conductivity	0.036	UTS	155
Resistivity	145	YP (0.2% offset)	145
Specific heat	0.120	Elongation (2 in.)	13.5
Magnetic properties	none	Modulus of elasticity	16.7
Coefficient of expansion	8.6	Elastic limit	115
		Elastic limit/dens.	25
		Mod./dens.	3.63

TITANIUM 75A

Recommended Use:
RT – 5 – 1 yr
160 – 5 – 1 yr
Cycle 20

Hardenable by cold work only. Ductile; weldable; good corrosion resistance.

Heat Treatment for: Maximum dimensional stability

Procedure:
Initial condition: bar rolled
Stress relieve 600°F, 1 hr, air cool
or 400°F, 1 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	4.51	Hardness	90B
Thermal conductivity	0.022	UTS	80
Resistivity	56.0	YP (0.2% offset)	70
Specific heat	0.125	Elongation (2 in.)	15
Magnetic properties	none	Modulus of elasticity	15.5
Coefficient of expansion	8.6	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	3.32

ELGILOY

Recommended Use: Very high elastic limit. Very high fatigue strength. Springs and suspensions.

Heat Treatment for: Maximum physical properties

Procedure:
As received wire or strip
flat – 900°F – 5 hr, air cool
wire – 900°F – 5 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	8.3	Hardness	50C
Thermal conductivity		UTS	340
Resistivity	100	YP (0.2% offset)	300
Specific heat		Elongation (2 in.)	
Magnetic properties	none	Modulus of elasticity	29.5
Coefficient of expansion	12.7	Elastic limit	~250
		Elastic limit/dens.	27.7
		Mod./dens.	3.55

TITANIUM 150A

Recommended Use:
RT – 0 – 1 yr
160 – 0 – 1 yr
Cycle – 5

Good corrosion resistance; high strength to weight. Hardenable by heat treatment.

Heat Treatment for: Maximum dimensional stability

Procedure:
1550°F, 1/2 hr, air cool (normalize)
1550°F, 1/2 hr, oil quench
Stress relieve 600°F, 1 hr, air cool

Physical Properties:		Mechanical Properties:	
Density	4.61	Hardness	35C
Thermal conductivity	0.037	UTS	160-175
Resistivity	80	YP (0.2% offset)	120
Specific heat	0.129	Elongation (2 in.)	15
Magnetic properties	none	Modulus of elasticity	16
Coefficient of expansion	6.2	Elastic limit	approx 75
		Elastic limit/dens.	36.5
		Mod./dens.	3.47

TANTALUM

Recommended Use: Ductile, high corrosion resistance, as rectifier plate.

Heat Treatment for: Annealed

Procedure: Annealed in vacuum 1920°F

Physical Properties:		Mechanical Properties:	
Density	16.6	Hardness	40E
Thermal conductivity	0.130	UTS	50
Resistivity	13.5	YP (0.2% offset)	
Specific heat	0.034	Elongation (2 in.)	60
Magnetic properties	none	Modulus of elasticity	27
Coefficient of expansion	6.5	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	1.65

TABLE A-12. (Continued)

TIN

Recommended Use: None

Heat Treatment for: None

Procedure: Pure – annealed

Physical Properties:		Mechanical Properties:	
Density	7.3	Hardness	[illegible] (20°C)
Thermal conductivity	0.155	UTS	1800 (20°C)
Resistivity	12.8	YP (0.2% offset)	nil
Specific heat	0.054	Elongation (2 in.)	700 (20°C)
Magnetic properties	none	Modulus of elasticity	6.0
Coefficient of expansion	23.5	Elastic limit	nil
		Elastic limit/dens.	
		Mod./dens.	9.3

GYRO MET (MALLORY)

Recommended Use: High density. Best of three types in mechanical properties.

Heat Treatment for: None

Procedure: None

Physical Properties:		Mechanical Properties:	
Density	16.7-17.05	Hardness	30-36
Thermal conductivity	0.235	UTS	135
Resistivity	12.45	YP (0.2% offset)	114
Specific heat	0.032	Elongation (2 in.)	2
Magnetic properties	none	Modulus of elasticity	44
Coefficient of expansion	5.80	Elastic limit	62
		Elastic limit/dens.	4.06
		Mod./dens.	2.6

SILVER (PURE)

Recommended Use: Electrical; optical film

Heat Treatment for: Relief of working strains

Procedure: 575°F anneal

Physical Properties:		Mechanical Properties:	
Density	10.5	Hardness	27VPN
Thermal conductivity	1.00	UTS	22.9
Resistivity	1.6	YP (0.2% offset)	7985
Specific heat	0.056	Elongation (2 in.)	54
Magnetic properties	none	Modulus of elasticity	11
Coefficient of expansion	19.1	Elastic limit	670
		Elastic limit/dens.	0.00635
		Mod./dens.	1.05

BERYLLIUM (QMV BRUSH)

Recommended Use:
RT – 0 – 3 m
160 – 4 – 3 m
Cycle – 20

High modulus to density ratio. Moderate elastic limit/density.

Heat Treatment for: Dimensional stability not established. No heat treatment.

Procedure: Hot pressed

Physical Properties:		Mechanical Properties:	
Density	1.85	Hardness	70-85B
Thermal conductivity	0.40	UTS	[illegible]
Resistivity	4-6	YP (0.2% offset)	~44
Specific heat	0.30-0.41	Elongation (2 in.)	10*
Magnetic properties	none	Modulus of elasticity	44.5
Coefficient of expansion	11.5	Elastic limit	12.0
		Elastic limit/dens.	10.8
		Mod./dens.	23.2

MALLORY 1000

Recommended Use: High density material

Heat Treatment for: None

Procedure: None

Physical Properties:		Mechanical Properties:	
Density	16.7	Hardness	24-30C
Thermal conductivity	0.275	UTS	94-112
Resistivity	12.45	YP (0.2% offset)	75
Specific heat	0.032	Elongation (2 in.)	2.5
Magnetic properties	none	Modulus of elasticity	46
Coefficient of expansion	5.6	Elastic limit	35
		Elastic limit/dens.	1.?
		Mod./dens.	2.4

GOLD

Recommended Use: Electrical properties; density.

Heat Treatment for: None

Procedure: Pure – wrought, annealed

Physical Properties:		Mechanical Properties:	
Density	19.3	Hardness	25 BHN 500 Kg. load
Thermal conductivity	0.70	UTS	19
Resistivity	2.35	YP (0.2% offset)	nil
Specific heat	0.031	Elongation (2 in.)	45
Magnetic properties	none	Modulus of elasticity	11.4
Coefficient of expansion	14.1	Elastic limit	nil
		Elastic limit/dens.	
		Mod./dens.	0.6

TABLE A-12. (Continued)

GE HEVIMET

Recommended Use:
RT – 8 – 1 yr
50 – 9 – 1 yr
Cycle – 5

High density. Tungsten powder, metal binder.

Heat Treatment for:
Maximum stability as received.

Procedure:
As received.

Physical Properties:		Mechanical Properties:	
Density	16.9-17.2	Hardness	20-30C
Thermal conductivity	0.225	UTS	95
Resistivity	6.0	YP (0.2% offset)	75
Specific heat	0.032	Elongation (2 in.)	2
Magnetic properties	none	Modulus of elasticity	50
Coefficient of expansion	5.6	Elastic limit	27
		Elastic limit/dens.	1.59
		Mod./dens.	2.94

FANSTEEL NO. 77

Recommended Use:
As a high density material. Stability not established.

Heat Treatment for:
Maximum dimensional stability

Procedure:
As received – no heat treatment

Physical Properties:		Mechanical Properties:	
Density	17	Hardness	30C
Thermal conductivity	0.226	UTS	105
Resistivity	12.3	YP (0.2% offset)	85
Specific heat	0.032	Elongation (2 in.)	5.5
Magnetic properties	none	Modulus of elasticity	40
Coefficient of expansion	6.5	Elastic limit	30
		Elastic limit/dens.	1.766
		Mod./dens.	2.35

COIN SILVER

Recommended Use:
Precipitation hardening alloy for good strength and conductivity.

Heat Treatment for:
Maximum electrical and strength

Procedure:
Quench and age

Physical Properties:		Mechanical Properties:	
Density	~ 10	Hardness	65B
Thermal conductivity	~ 1	UTS	55
Resistivity	1.8	YP (0.2% offset)	
Specific heat	~ 0.056	Elongation (2 in.)	8
Magnetic properties	none	Modulus of elasticity	11
Coefficient of expansion	~19	Elastic limit	
		Elastic limit/dens.	
		Mod./dens.	1.1

TUNGSTEN CARBIDE (94WC-6Co)

Recommended Use:
Very high hardness. Tools, pivots, bearing surfaces.

Heat Treatment for:
None

Procedure:
None

Physical Properties:		Mechanical Properties:	
Density	14.8	Hardness	90-92A
Thermal conductivity	0.19	UTS	Compression 680-750
Resistivity	20	YP (0.2% offset)	
Specific heat	0.05	Elongation (2 in.)	
Magnetic properties	none	Modulus of elasticity	88
Coefficient of expansion	5	Elastic limit	Compression 625
		Elastic limit/dens.	Compression 42.3
		Mod./dens.	5.95

MAGNESIUM NICKEL SILVER ALLOY

Recommended Use:
Contact and electrical. Good conductivity, wear resistance and strength. Better creep strength than coin silver.

Heat Treatment for:
Maximum stability and electrical

Procedure:
Annealed – hardened by air heating at 1200-1475 for a time and at a temperature which is a function of thickness.

Physical Properties:		Mechanical Properties:	
Density	10.5	Hardness	89 (30T)
Thermal conductivity	0.75	UTS	65-68
Resistivity	2.32	YP (0.2% offset)	55-56
Specific heat	0.05	Elongation (2 in.)	1-3
Magnetic properties	none	Modulus of elasticity	12
Coefficient of expansion	19	Elastic limit	45-46
		Elastic limit/dens.	4.39
		Mod./dens.	1.14

Data From "An Investigation of the Precision Mechanical Properties of Several Types of Beryllium",

by T. J. Hughel, Research Staff Report, General Motors Laboratory, Report No. MR-120, April 4, 1960

This report discusses the mechanical properties of beryllium of importance to gyro applications, and presents data on precision elastic limit, microcreep limit, and the dimensional stability* under stress for several grades of commercial beryllium.

TABLE A-13. AVERAGE PRECISION ELASTIC-LIMIT DATA FOR VARIOUS GRADES OF COMMERCIAL BERYLLIUM

Mesh	Composition	Average Precision Elastic Limit, psi
-200	100% virgin	2200
-200	Standard production grade	2663
-200	60% recycle + 40% virgin	4100
-200	100% recycle	4300
Subsieve	100% virgin	4333
-325	100% virgin	6500
-200	Dispersed iron alloy	6833
Subsieve	100% recycle	11167

TABLE A-14. DATA ON PRECISION ELASTIC LIMIT, ELASTIC MODULUS, AND MICROCREEP LIMIT FOR SPECIMENS OF COMMERCIAL BERYLLIUM

Mesh	Composition	%BeO (GMR)	%BeO (Brush)	Grain Size, microns (GMR)	Grain Size, microns (Brush)	Density, g/cc (GMR)	Density, g/cc (Brush)	PEL, psi	Elastic Modulus, million psi	MCL, psi
-200	100% recycle	2.67	2.19	11.3	19	1.866	1.858	4,000	44	7,500
-200	Ditto	2.67	2.19	11.3	19	1.866	1.858	3,500	45.2	10,500
-200	"	2.93	2.26	8.7	20	1.861	1.854	5,500	43.6	6,000-13,000
-200	"	2.93	2.28	8.7	20	1.861	1.854	5,000	46	7,900
-110	"	2.92	2.68	13.6	21	1.867	1.855	4,500	43.4	5,000
-110	"	2.92	2.68	13.6	21	1.867	1.855	3,300	40.3	7,500
-110	100% virgin	1.39	1.03	15.1	21	1.859	1.856	4,500	45.3	4,700
-110	Ditto	1.39	1.03	15.1	21	1.859	1.856	1,200	36	1,600
-110	"	1.55	1.28	16.6	21	1.849	1.846	2,100	42.4	4,500
-110	"	1.55	1.28	16.6	21	1.849	1.846	1,500	36	4,500
-110	"	1.28	1.06	--	21	1.860	1.851	2,500	44	7,000
-110	"	1.28	1.06	--	21	1.860	1.851	1,750	39.6	4,500
-110	60% recycle 40% virgin	2.18	2.48	10.97	22	1.860	1.855	7,500	39.6	8,000
-110	Ditto	2.18	2.48	10.97	22	1.860	1.855	800	--	12,500
-110	"	2.41	3.31	--	20	1.862	1.863	4,500	49.5	9,500
-110	"	2.41	3.31	--	20	1.862	1.863	3,000	42.1	9,250
-110	"	2.37	2.31	11.55	19	1.845	1.851	6,700	43.5	6,700
-110	"	2.37	2.31	11.55	19	1.845	1.851	2,500	37.1	9,000
-325	100% virgin	2.80	2.35	--	20	1.861	1.858	7,000	44	7,000
-325	Ditto	2.80	2.35	--	20	1.861	1.858	5,000	43.1	11,500
-325	"	1.80	2.11	11.05	16	1.854	1.853	6,500	46.4	9,000
-325	"	1.80	2.11	11.05	16	1.854	1.853	7,000	44.9	11,500
-325	"	1.92	2.29	9.3	17	1.860	1.849	6,500	45	7,000
-325	"	1.92	2.29	9.3	17	1.860	1.849	7,000	44.3	7,500
S. S.	100% recycle	6.01	5.89	--	10	1.879	1.855	16,000	44	17,700
S. S.	Ditto	6.01	5.89	--	10	1.879	1.855	9,500	47.8	25,800
S. S.	"	6.38	5.50	5.86	10	1.877	1.876	11,000	47.2	23,500
S. S.	"	6.38	5.50	5.86	10	1.877	1.876	8,500	43.04	29,500
S.	"	6.08	5.70	--	10	1.881	1.876	10,000	45.4	21,500
S. S.	"	6.08	5.79	--	10	1.881	1.876	12,000	44.5	19,500
-200	Dispersed-Phase Fe Alloy	1.68	1.75	--	17	1.872	1.855	5,000	41.7	8,700
-200	Ditto	1.68	1.73	--	17	1.872	1.855	9,000	43.6	13,700
-200	"	2.15	2.01	--	21	1.803	1.870	7,500	43.7	14,000
-200	"	2.15	2.01	--	21	1.803	1.870	7,500	44.6	12,500
-200	"	1.77	1.66	--	25	1.878	1.861	6,000	40.3	12,500
-200	"	1.77	1.66	--	25	1.879	1.861	6,000	42.3	9,500
S. S.	100% virgin	4.68	3.60	--	18	1.881	1.876	6,500	45.7	16,000
S. S.	Ditto	6.68	3.60	--	18	1.881	1.876	4,500	41.2	5,300-11,500
S. S.	"	3.38	2.79	--	16	1.874	1.859	6,000	44.4	14,000
S. S.	"	3.38	2.79	--	16	1.874	1.859	2,500	46.5	11,500
S. S.	"	2.91	3.17	--	15	1.859	1.858	4,000	50.3	6,000
S. S.	"	2.91	3.17	--	15	1.859	1.858	2,500	50.6	15,500

*The term "dimensional stability" as used here denotes slow plastic strain at stress levels below the precision elastic limit. This strain is more commonly denoted as creep.

TABLE A-15. DATA ON DIMENSIONAL STABILITY UNDER STRESS (CREEP) FOR COMMERCIAL BERYLLIUM

Mesh Size and Grade	Oxide Content, % GMR	Oxide Content, % Brush	Grain Size, μ GMR	Grain Size, μ Brush	Density, g/cc GMR	Density, g/cc Brush	Test Stress, psi	Total Test Time, hrs	Total Strain, μ-in. in.	Remarks
-200, 100% recycle	2.67	2.17	11.3	19	1.866	1.858	3,600	508.5	+ 6.9	
Ditto	2.93	2.28	8.7	20	1.861	1.854	5,200	468.5	+ 6.6	
"	2.92	2.68	13.6	21	1.867	1.855	3,400	470.5	+97.5	Specimen stress relieved and retested
-200, 100% virgin	1.39	1.03	15.1	21	1.859	1.856	3,800	803	+41.4	Ditto
Ditto	1.55	1.28	16.6	21	1.849	1.846	1,700	347	+ 7.2	
"	6.95*	1.06		21	1.860	1.851	1,665	420	- 2.9	*% BeO redetermined to be 1.28%
-200, 60% recycle -200, 40% virgin	2.18	2.48	10.97	22	1.860	1.855	3,940	97	+20.6	Specimen stress relieved and retested
Ditto	2.41	3.31*		20	1.862	1.863	2,800	556.5	+ 3.0	*Reported to be higher because of proximity to surface of pressing
"	2.37	2.31	11.55	19	1.845	1.851	2,400	560	+ 6.8	
-325, 100% virgin	2.80	2.35		20	1.861	1.858	4,800	555	+10.8	
Ditto	1.80	2.11	11.65	16	1.854	1.853	6,200	137.5	+34.6	
"	1.92	2.29	9.3	17	1.860	1.849	6,400	489	+10.1	
Subsieve 100% recycle	6.01	5.89		10	1.879	1.855	12,100	490.5	+87.2	Specimen stress relieved and retested
Ditto	6.38	5.50	5.86	10	1.877	1.876	9,260	420	+ 2.9	
"	6.08	5.70		10	1.881	1.876	10,450	418	+ 4.7	
+200 (see [illegible])	1.68	1.71		17	1.872	1.855	6,750	420	+ 6.8	Dispersed phase Fe alloy
Ditto	5.69*	2.01		21	1.803	1.870	7,125	359	+12.3	Ditto *% BeO redetermined to be 2.15%
"	1.77	1.66		25	1.878	1.861	5,700	359	+12.6	"
Subsieve 100% virgin	4.48	3.60		18	1.881	1.876	5,340	431.5	+10.3	
Ditto	3.38	2.79		16	1.874	1.859	4,040	359	+13.8	
"	2.91	3.17		15	1.859	1.858	3,090	359	+ 0.3	
Commercial		1.73	15.1	22	1.861	1.856	500	384	+ 2.0	
Ditto		1.75		22	1.868	1.858	1,900	384	+ 3.7	
"		1.70	12.8	22	1.855	1.858	1,440	525.5	+ 8.2	
"	1.57	1.45	9.25	21	1.842	1.842	4,500	829	+ 9.9	
"	1.44	1.47	10.1	21	1.844	1.842	4,300	466	+ 9.3	
"	1.39		11.5	21	1.842	1.842	950	359	+ 0.2	
"	1.41	1.47	10.1	21	1.844	1.842	4,280	431.5	+ 8.0	
-200, 100% recycle	2.92	2.68	13.6	22	1.867	1.855	3,140	529	+ 3.7	2nd test
-200, 100% virgin	1.39	1.03	15.1	21	1.859	1.856	1,140	695	+26.3	Ditto
-200, 60% recycle -200, 40% virgin	2.18	2.48	10.97	22	1.804	1.855	3,940	383	+ 5.3	"
Subsieve 100% recycle	6.01	5.89		10	1.809	1.855	12,100	383	+11.1	"

Data From "Gage Blocks of Superior Stability III: The Attainment of Ultrastability"

by

M. R. Meyerson and M. C. Sola,
Trans. ASM, 57, 164 (1964)

This paper discusses the procedures used in the gage-block program at the National Bureau of Standards for the attainment of a very high degree of dimensional stability. It summarizes the data for a number of materials considered suitable for use as gage blocks; as the results show, several of these are very stable indeed. The test specimens used all have a 2-inch gage length, and a cross section 1-3/8 by 3/8 inch.

TABLE A-16. SUMMARY OF STABILITY CHARACTERISTICS OF ALL GAGE

Type[a]	Symbol	Surface hardness,[b] R_C	Material and identifying treatment	Max period observed, months
3	P	>70	17-4 PH, hardened, aged, nitrided	22
4[c]	KA	72	Titanium carbide, 25% Ni, stress relieved	20
2	F	68	410, annealed core, nitrided	45
4	S	65	Titanium carbide, steel binder, hardened and tempered	19
2	L	66	1010, pack carburized, case hardened	30
1[d, e]	T	62	52100, directly quenched or martempered, stabilized, R_C 62	49
3	N	68	Nitralloy 135 mod, hardened, tempered, nitrided	34
2	L	65	1010, carbonitrided, case hardened	20
3	N	68	Nitralloy 135 mod, hardened, tempered, nitrided	34
1[d, e]	T	60	52100, directly quenched or martempered, stabilized, R_C 60	50
2	F	67	410, annealed core, nitrided 2-step	45
3	N	57-69	Nitralloy 135 mod, hardened, tempered, liquid nitrided	17
2[f]	T	68	52100, annealed, chromium plated	48
2	L	62	1010, annealed core, thermal sprayed	17
1[d]	V	62	T15, hardened, tempered to R_C 62	19
3	E	66	8620, carbonitrided, case hardened	30
1[d]	T	65	52100, directly quenched or martempered, stabilized, R_C 65	49
4	AL & NBS	>68	Chromium carbide, Ni binder, as received	20
2[c]	L	68	1010, annealed core, chromium plated	25
4	Q	>70	Aluminum oxide, no binder	29
3	E	65	8620, liquid carburized, case hardened	32
2	N	68	Nitralloy 135 mod, annealed core, nitrided	17
2[f]	T	72	52100, annealed, flame plated	30
3	E	64	8620, gas carburized, case hardened	20
2	F	68	410, annealed core, nitrided	30
1[d]	V	65	T15, hardened, tempered to R_C 65	20
2[c]	L	68	1010, annealed core, chromium plated	36
1[d]	W	65	W4, hardened, stabilized	16
1[d]	. . .	65	Commercial through-hardened steel gage blocks, AA grade	25
4	KB	68	Titanium carbide, 40% Ni, stress relieved	19
3[e]	C	65[g]	420, hardened, tempered, nitrided	16
2	D	65	D2, annealed core, nitrided	16
2	F	68	410, annealed, chromium plated	24
1[d]	D	58	D2, hardened, stabilised	16
2	D	72	D2, annealed, flame plated	24
2	F	72	410, annealed, flame plated	23
1[d]	T	66	52100, hardened, deliberately unstable	7

a Type 1 is through-hardened; Type 2 has annealed cores and hardened surfaces; Type 3 has partially hard or cermet.

b This value represents hardness of the case or coating where applicable. Where appropriate, hardness converted to R_C.

c Only one specimen of this type tested.

d Results reported were obtained previously and reported in a prior reference (9). They are included for

e Contained short-term periods of greater instability.

f Average of two blocks with widely different values. One block was very stable.

g Estimated.

ACTERISTICS OF ALL GAGE BLOCKS, IN ORDER OF MERIT

nt	Max period observed, months	Fabrication of case on nongaging faces: Intact	Partially removed	Completely removed	Not applicable	Average change in length, μ-in./in./yr
	22			X		+ 0.05
	20				X	- 0.07
	45		X			+ 0.10
d tempered	19				X	- 0.10
	30		X			+ 0.11
tabilized, R_C 62	49				X	- 0.13
ided	34		X			+ 0.17
	20			X		+ 0.17
ided	34			X		+ 0.19
tabilized, R_C 60	50				X	+ 0.20
	45	X				+ 0.20
d nitrided	17			X		+ 0.21
	48		X			+ 0.21
	17			X		+ 0.25
	19				X	+ 0.27
	30			X		+ 0.29
tabilized, R_C 65	49				X	- 0.30
	20				X	- 0.34
	25		X			+ 0.35
	29				X	+ 0.38
	32			X		+ 0.38
	17			X		+ 0.40
	30			X		+ 0.41
	20			X		+ 0.42
	30			X		+ 0.44
	20				X	+ 0.49
	36			X		+ 0.58
	16				X	+ 0.59
ks, AA grade	25				X	- 0.67
	19				X	- 0.78
	16			X		+ 0.80
	16		X			+ 0.81
	24			X		+ 0.85
	16				X	+ 0.86
	24			X		+ 0.89
	23			X		+ 0.96
	7				X	-25.0

aces; Type 3 has partially hardened cores and hardened cases; Type 4 is a ceramic

Where appropriate, hardness was measured with a micro-tester such as the Vickers and

ce (9). They are included for comparison.

table.

LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963
166	Literature Survey on the Effect of Sonic and Ultrasonic Vibrations in Controlling Grain Size During Solidification of Steel Ingots and Weldments, May 15, 1963
167	Notes on Large-Size Furnaces for Heat Treating Metal Assemblies, May 24, 1963 (A Revision of DMIC Memo 63)
168	Some Observations on the Arc Melting of Tungsten, May 31, 1963
169	Weldability Studies of Three Commercial Columbium-Base Alloys, June 17, 1963
170	Creep of Columbium Alloys, June 24, 1963
171	A Tabulation of Designations, Properties, and Treatments of Titanium and Titanium Alloys, July 15, 1963
172	Production Problems Associated with Coating Refractory Metal Hardware for Aerospace Vehicles, July 26, 1963
173	Reactivity of Titanium with Gaseous N_2O_4 Under Conditions of Tensile Rupture, August 1, 1963
174	Some Design Aspects of Fracture in Flat Sheet Specimens and Cylindrical Pressure Vessels, August 9, 1963
175	Consideration of Steels with Over 150,000 psi Yield Strength for Deep-Submergence Hulls, August 16, 1963
176	Preparation and Properties of Fiber-Reinforced Structural Materials, August 22, 1963
177	Designations of Alloys for Aircraft and Missiles, September 4, 1963
178	Some Observations on the Distribution of Stress in the Vicinity of a Crack in the Center of a Plate, September 18, 1963
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13. ABSTRACT

This memorandum discusses briefly the mechanisms leading to the dimensional instability of metals and alloys, together with some related phenomena: precision elastic limit, microcreep, and microstrain. Information of this type is needed in the design and manufacture of precision devices, such as bearings, gage blocks, gyros, accelerometers, and components of missile guidance systems.

Tables of data from available reports and papers are presented for a number of metals and alloys. These should provide a useful source of information for the selection and processing of metals for applications where a high degree of dimensional stability is required. (Author)

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